



Fuel consumption and pollutant emissions of heavy-duty trucks traversing signalized intersections: an exploration using real-world data

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Colophon and background information guide for this presentation

Presentation and report in one document

- This presentation is the final report for work package 4 “Impact assessment of use of Intelligent Traffic Light Controllers” in the CATALYST Living Lab program.
- The CATALYST Living Lab is a public-private partnership (PPP) jointly setup by the Ministry of Infrastructure and Water Management, Topsector Logistiek/TKI Dinalog, NWO and SIA. Over 40 parties work together in the CATALYST Living Lab to “develop and accelerate Connected Automated Transport innovations for safer, more efficient and sustainable heavy road transport”
- This presentation has been drafted at the request of the Provincie Zuid-Holland. Sponsor of the research is the Metropoolregio Rotterdam-Den Haag as part of the CATALYST Living Lab program.
- The research has been conducted by TNO, as coordinator/program manager of the CATALYST Living Lab (www.catalystlab.nl). Responsibility for the content of this presentation lies with TNO.

Sponsor	Client	Authors / CATALYST program
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Management summary

Heavy-duty trucks not having to stop at a signalized intersection avoid consuming a median 0.12 l of fuel, and avoid emitting a median 1.8 g of NO_x and 0.32 kg of CO_2 compared to a scenario where they would have to stop, based on data obtained from 5 trucks in real-world driving operations

As the second largest cost factor for a transport operator (after labor costs), there has been a significant effort in reducing the fuel consumption of diesel trucks. In the past decades, the intelligent traffic light emerged as a plausible way to reduce emissions and improve sustainability of road transportation. Modern intelligent traffic lights can not only prevent a vehicle from stopping, but also indicate an optimal speed to approach the intersection, and even provide priority for heavy-duty trucks. In order to assess the potential impact of these systems, good estimations of fuel consumptions and pollutant emissions at signalized intersections are required. Over the years, different figures have been estimated for fuel savings at an intersection attributed to various behaviors. The main question for this research therefore was formulated as follows:

What are the effects of heavy-duty trucks stopping or not stopping at signalized intersections on fuel consumption, CO_2 and NO_x emissions?

- In the current work we did not focus on actual priorities granted at the intersection but looked at vehicle speed profiles for heavy-duty trucks traversing signalized intersections, some of them in the Province of Zuid Holland.
- The fuel consumption and pollutant emissions were logged from the CAN bus and were physically measured at the exhaust (tailpipe) of 5 EURO VI-vehicles from one truck brand that traversed multiple intersections (for a total filtered sample of 902 intersections passages) while performing their actual daily operational tasks, that is, in real-world operations with mean vehicle combination weights of 38 tons.
- We statistically compared three clusters (driving scenarios): vehicles that must stop, vehicles that slow down and reduce their speed, and vehicles that do not change their speed at the traffic light.
- The difference between stopping and non-stopping at the signalized intersection amounts to a median saving of 0.12 l of fuel and 0.32 kg of CO_2 , for the 2000-meter trajectory under study across the logged signalized intersections
- The difference between stopping and non-stopping at the signalized intersection results in a median saving of 1.8 g NO_x for the 2000-meter trajectory under study across the logged signalized intersections
- Emissions of NH_3 were also investigated, but no reliable conclusions can be drawn due to erratic emissions caused by either low exhaust gas temperatures or high fluctuations due to complex control technology.

Contents of this presentation

Organized into separate sections in this document



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7 | Conclusions
and suggestions for
further research

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Current programs: Connected Transport Corridors and CATALYST

Collaboration between CTC and CATALYST for this impact assessment of fuel consumption and pollutant emissions of heavy-duty trucks at signalized intersections



Connected Transport Corridors

- Deployment program for data sharing and connectivity topics in the Netherlands
- Various technological use cases: smart traffic light controllers, data exchange, tire pressure monitoring, road works warnings
- Focus on deployment in actual operations, rather than testing/piloting, no end-time of the program
- Applying existing technology
- Separate departments in the Netherlands: Brabant/Limburg, Zuid-Holland, Amsterdam/Schiphol et cetera
- Led by the Ministry of IenW – Talking Logistics

<http://connectedtransportcorridors.nl>



CATALYST Living lab

- (Applied) scientific research-oriented, with pilots/tests/trials and impact assessments
- Public-private partnership sponsored by Ministry of IenW, NWO, TKI Dinalog SIA, supported by Talking Logistics
- Focusing on assessing existing and testing new Connected Automated Transport innovations
- Runtime: 2019 – 2023
- Coordinated by TNO
- Over 40 parties involved
- 12 work packages, around Connected and Automated Transport and their impacts on safety, sustainability and efficiency
- One work package on impact assessment of intelligent traffic lights on fuel consumption – this presentation

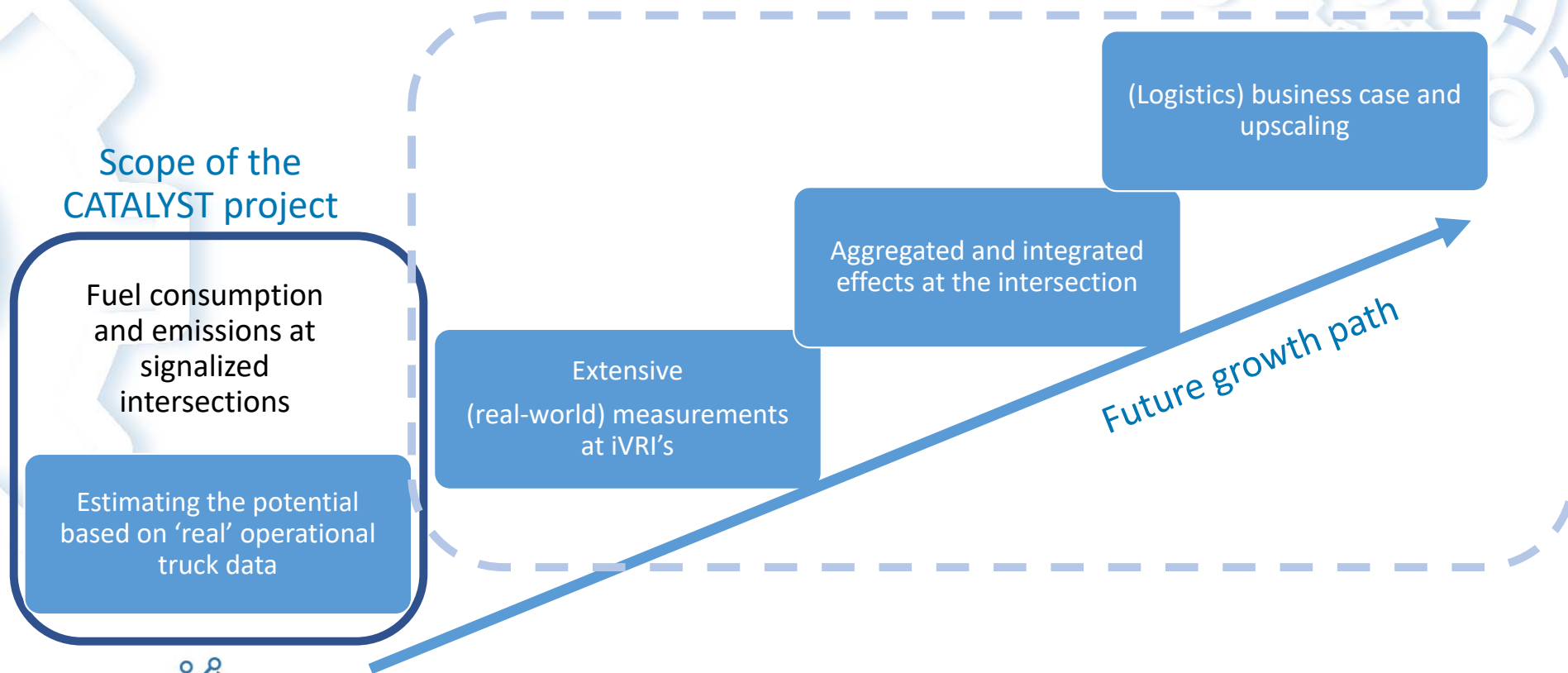
<http://catalystlab.nl>



The appendix contains two slide sets on the background on the Connected Transport Corridors Zuid-Holland and CATALYST programs

HEAVY DUTY TRANSPORT LIVING LAB

Scoping the current research to future research questions and opportunities



1 | Introduction and context

Intelligent connected traffic lights – iVRIs – have the ability to grant priority to heavy-duty trucks. It is the expectation that this results in fuel consumption and pollutant emissions reductions. This introductory section sets the scene providing some general background on the iVRI technology and past and present researches regarding fuel consumption and pollutant emissions for heavy-duty trucks at signalized intersections.

Background: development and implementation of iVRI/iTLI

Definition of an iVRI / iTLI

An important development within traffic management is the development and deployment of a new generation of traffic control systems, the Intelligent Traffic Light Installations (iTLLs), sometimes referred to as iTLCs (controllers), or as iVRIs (intelligente verkeersregelinstallatie)* in the Netherlands. iVRIs constantly communicate with arriving vehicles through the clouds of multiple service providers using a combination of detector loop sensor data and short and long-range communication using Cooperative-ITS (C-ITS) message sets. Using this data, traffic light controllers at the intersection level are able to control the signal phases and timings more efficiently. At corridors or on a network level multiple co-operating intelligent traffic lights will be able to dynamically optimize their control strategy to increase road capacity and prevent traffic congestion. This allows a road authority to better optimize traffic flows towards various goals, such as safety, livability, sustainability and traffic flow.

The main features of an iVRIs:

- The iVRI enables communication between traffic light and road user (both ways).
- By using individual road user data (an additional source of information in addition to existing detection loops), an iVRI can better attune the control strategy to the current traffic situation.
- The iVRI provides data for information services. These services use the iVRI data to inform and / or advise road users.
- The iVRI gives the road authority more options to regulate traffic based on a variety of policy goals.

* = please note, throughout the remainder of this presentation, we use the Dutch acronym **iVRI** to refer to iTLLs/iTLCs as that term is much more prevalent in the Netherlands and it avoids confusion.

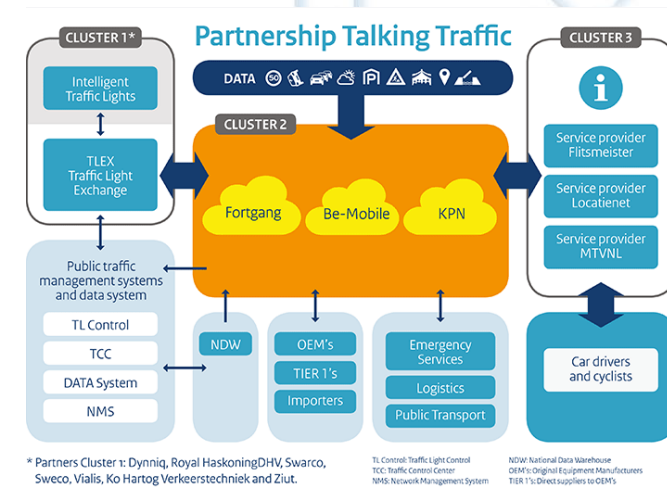
Available services at an iVRI

iVRI use cases

An iVRI is suitable for several applications: prioritizing, informing and optimizing. In the Netherlands, iVRIs are developed as part of the Partnership Talking Traffic. In the Talking Traffic program these applications are called Use Cases and can be described as traffic functions that an iVRI can have:

- **Prioritization:** concerns the prioritization of specific target groups at traffic lights, such as emergency services, regular buses, groups of cars and (groups of) trucks. This can also be done on specific lanes
- **Informing:** concerns the in-car provision of current information from the iVRI or information from the in-car system that is (partly) based on information from the traffic light controller,
- **Optimizing:** concerns the optimization of the signal phases and timings at one or more intersections by making data from vehicles available to the traffic light controller.

The **Prioritization** use case is mostly relevant for this CATALYST iVRI work package, as it involves the prioritization of heavy-duty trucks as a potential measure to reduce fuel consumption and pollutant emissions.



Expected impacts of the iVRI

Subject of this research: impact on fuel consumption and pollutant emissions

In general (within all three iVRI use cases) the amount of stops and the speed variability is decreased which will result in a smoother overall traffic flow. This translates into less stationary traffic and subsequently lower fuel consumption and pollutant emissions. Therefore it is expected that iVRIs contribute to improved traffic safety, traffic flow (throughput), less emissions, and improved efficiency.

For the Prioritization use case; traffic lights cause heavy-duty vehicles (trucks) to slow down, which causes extra fuel consumption and leads to higher emissions. iVRIs can communicate with oncoming traffic, can "recognize" upstream traffic and give priority to these specific vehicle types. This reduces stops, speed variability and smooths the vehicle trajectory, and more specifically, reducing the acceleration of a vehicle can significantly reduce the fuel consumption and emissions. Understanding the size / order-of-magnitude of that effect is the aim of this research.

Previous studies regarding fuel consumption and emissions at signalized intersections

A decade of results in overview

Date	Project	Location	Trucks	Intersections	Priority	Advisory	Fuel method	Result
2010-2012	Freilot	EU (4 locations)	124	38			Estimated	1%, 8%, 13% Dep. on location
2013-2015	Compass4D	EU (7 locations)	45	56	Only in one location	In many locations	Measured and modelled	5-10 % savings overall, 20 to 60 g CO ₂ /km.
2017-2018	C-TheDifference	Helmond	103	24	Yes	Yes	Modelled	-
2018	Experience week Connected Transport	Netherlands (4 locations)	250	-	Yes	Yes	-	6-14% platooning and 10-17% platooning on green wave (anecdotal)
2018-	Talking Traffic / Connected Transport Corridors	Netherlands	-	-	No	No	-	1 l per stop (anecdotal, p 23 - 25)

- Various studies have been conducted in the past, as shown in the table. Designs of studies typically vary and consequently types of analyses do as well. The heterogeneity in the measurement methods makes the results hard to compare and results are often aggregated. Nonetheless the final column in the table shows some indicative results with regards to fuel consumption, for which it is apparent that attention has only been given to fuel consumption and corresponding CO₂ emissions, rather than for instance nitrogen oxides (NO_x) or particulates. Also, most historic and ongoing studies have focussed on the 'effects on traffic', only a few studies have included fuel consumption and sustainability. Until now, we are not aware of projects having measured 'at the tailpipe'.
- In the literature, we found some references regarding NO_x emissions. Numerical models typically predict over 10% reduction in NO_x emissions when implementing traffic management methods to reduce stops (i.e. green waves). For instance:
 - Guardiola et al. 2019 (Spain use case) 13-32% NO_x reduction
 - Madireddy et al. 2011 (Belgium use case) 10% NO_x reduction
 - Brehmer et al. 2003 (USA use case) 9-12% NO_x reduction

Scope: regular (non-connected) signalized intersections are included in this study

The iVRIs were not operational during data collection

- In the following CATALYST analysis we include regular (non-connected) signalized intersections. The main argument here is that while some of the iVRIs in the Province of Zuid Holland would already be able to provide priority to trucks, capturing this information is quite challenging. In preparation of this study, the Province concluded that the available data structures were not yet sufficient for such an analysis.
- A future field-operational test could try to close the loop in terms of connectivity and data capture (such that priority requests and priorities granted are properly logged) to estimate how often a truck receives priority in real-world operations.
- This research studies the vehicle behavior at 'traditional' non-connected traffic signals which serves as a viable approach to study the potential benefits in terms of fuel consumption and emissions for the Prioritization use case at iVRIs in the future.



2 | Research questions and methodology

This section of the presentation provides the main research question and a global overview of the methodology for this research including dataset background and modelling approach

Motivation for research question

Providing insights in societal and business impacts of heavy-duty trucks at signalized intersections

- As more iVRIs are deployed across the Netherlands, the question comes up what the societal and business value is of such intelligent traffic lights. The Province of Zuid Holland recognizes this and therefore motivated the present research to investigate the fuel consumption and CO_2 emissions and pollutant (NO_x) emissions reductions at signalized intersections when trucks do not have to stop at the intersection, which would be a potential outcome of heavy-duty trucks requesting priority at the iVRIs deployed.
- Additionally, more and more companies are offering subscription-based services (such as GreenFlowForTrucks and TruckMeister) that allow trucks to connect to iVRIs and request priority at traffic lights. Since these subscription-based services involve a cost for transport companies, the question arises to what extent companies are able to capture value from their investment. The present research won't answer the latter question definitively (as it depends on many more factors) but provides some first evidence about the effect-sizes of avoided stops regarding fuel consumption reductions which would translate in business value.

Research questions

The main question is formulated as follows:

What are the effects of heavy-duty trucks stopping or not stopping at signalized intersections on fuel consumption, CO_2 and NO_x emissions?

Sub research questions:

- What are the fuel consumption, CO_2 and NO_x emissions produced by stopping at an intersection compared to not stopping and continuing driving?
 - What effect do various speed profiles (full stop, slow down and continuous driving) have on this difference?
-
- Please note – fuel consumption has a 1:1 relationship with CO_2 emissions, and therefore by referring to fuel consumption in the analyses, we are also referring to CO_2 emissions, and vice-versa. We use the diesel tank-to-wheel (TTW) conversion factor of 2.618 kg CO_2 per liter of diesel derived from JRC TTW report Version 4.a (Report EUR 26241 EN) available at <https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/tank-wheels-report-version-4a-well-wheels-analysis-future-automotive-fuels-and-powertrains>

Methodological starting point for the research question in this study

Using the 'TKI Integrator Connected Truck Trials' datasets

- In 2019-2020 the 'TKI Integrator Connected Truck Trials' project has been conducted in which multiple heavy-duty vehicles, in their normal daily operation, have been equipped with extensive measurement equipment.
- Main aim of that project was to research the effect and impact of Adaptive Cruise Control, as an Advanced Driver Assistance System, on the fuel consumption, emissions and driver behavior. Within various driving campaigns drivers were, while driving on highways, requested to enable and disable the ACC and drive with different ACC settings. While the Integrator CTT mainly focused on the data on highways the monitoring systems were also active at the lower level road network (provincial, local), this dataset from these vehicles of 25 weeks provides an opportunity to investigate the fuel consumption and emissions at signalized intersections.
- For this study, we reuse this Integrator CTT dataset. In the following slides, we provide more background on the dataset and we detail the data processing used.

Multiple approaches for collecting (observed) data to provide an answer to the research question

This research uses a combination of data from a field-operational test and naturalistic driving study – from the earlier Integrator CTT project

Experiments under controlled circumstances, depending on the safety aspects in closed areas (test tracks) or on the public road. Often requires rigorous planning and can only be conducted for small period.

Controlled experiments

CATALYST iVRI work package powered by Integrator CTT dataset

A FOT is mainly conducted to evaluate new (vehicle) techniques and products, this usually implies that subjects drive with the system to be studied turned on (compulsorily) for a certain period, as well as turned off (compulsorily) for a certain period.

Field operational test

Observing road users' everyday driving behaviour. The observations takes place during normal everyday drives in (preferably) drivers' own vehicles without instructions or inventions

Naturalistic driving

Integrator Connected Truck Trials background

General information about the previous project that provides the dataset for this CATALYST iVRI study

- 6 transport companies were involved
- In total the vehicles were logged for a duration of 25 weeks.
- 11 professional truck drivers were involved
- 10 heavy duty trucks were equipped with logging instruments, 9 trucks remained in final dataset with 5 trucks measuring pollutant emissions at the exhaust
- ~ 353.000 kilometer were logged in total
- ~ 100.000 liters diesel has been consumed during the total duration of the project.
- ~ 274.000 kilometer were registered at the highways and provincial roads (>75km/h)
- 6800 hours of data has been recorded (>30TB)



Relevant variables (parameters / data fields)

In relation to the main research question the following variables are considered to be of influence and interest and should be taken into account, either implicitly or explicitly.

The next slide shows how these variables are taken into account in the Integrator CTT dataset.

Classification of system variables	
Environmental	Weather
	Traffic
	Wind
Human behavior	Reaction time
	Throttle/brake balance
	Other driving practices
Truck	Engine properties
	Load
	Engine temperature
	Catalyst status (exhaust gas cleaning)
Intersection	Intersection geography and location
Outcome measure	Velocity
	Fuel Rate

Linking the Integrator CTT dataset to the system variables

The table shows the presence of system variables in the Integrator CTT dataset

Classification of system variables		Integrator CTT dataset
Environmental	Weather	Indirectly observed
	Traffic	Indirectly observed
	Wind	Indirectly observed
Human behavior	Reaction time	Unobserved
	Throttle/brake balance	Controlled
	Other driving practices	Unobserved
Truck	Engine properties	Controlled
	Load	Indirectly observed
	Engine temperature	Measured
	Catalyst status (exhaust gas cleaning)	Controlled
Intersection	Intersection geography and location	Observed
Outcome measure	Velocity	Measured
	Fuel Rate	Measured

The overall methodology for this research in summary

Research Question

What are the effects of heavy-duty trucks stopping or not stopping at signalized intersections on fuel consumption, CO_2 and NO_x emissions?

Approach

Analyze crossings of signalized intersections using real-world data from heavy-duty trucks

Using the data collected in the Integrator Connected Truck Trials project (a field-operational test with naturalistic driving elements)

Analysis

Using the Integrator CTT data set and defining scenarios, applying cluster analysis, and perform statistical tests

Result & impact

Provide an answer to the research question:
Determination of the upper bound for savings values of fuel consumption, CO_2 and NO_x at signalized intersections



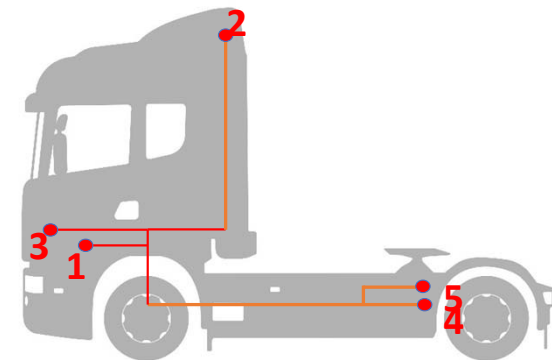
3 | Data collection and dataset preprocessing

This section details the data collection approach and the enrichment of iVRI passages-data from the main dataset

Details of the Integrator CTT dataset: vehicle CAN bus logging combined with physical measurements in exhausts

Using TNO's SEMS measurement platform

- SEMS measurement systems were installed in 10 DAF trucks from 6 transport companies collecting data for 25 weeks in the TKI Integrator Connected Truck Trials project running from Q3/2019 to Q1/2020.
- Out of those 10 trucks, in 5 trucks the SEMS measurement systems have logged vehicle telematics from the CAN bus as well as pollutant emissions at the tailpipe.
- All 5 trucks are Euro VI, rated power between 320-350 kW.
- Data collection started at ignition-on and data was being uploaded at ignition-off to a secured TNO database environment.
- Data can be processed and enriched by means of additional (post trip) algorithms.



Fuel consumption and emission logging

SEMS	
CAN bus	(1)
GPS	(2)
Pressure sensor	(3)
Temperature sensor	(4)
Exhaust sensors NO _x , O ₂ , NH ₃	(5)



More info about SEMS | <https://www.tno.nl/sems>



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Information about the trucks in the dataset

Focusing on one specific brand and model

- To facilitate large-scale data logging, the TKI Integrator CTT project only focused on trucks from the DAF brand. This minimized the work needed for translating and interpreting the CAN bus data.
- Five DAF XF vehicles (ranging from DAF XF 440, DAF XF 460 to DAF XF 480) with model years > 2015 were equipped with SEMS including measurement sensors installed in the exhaust (tailpipe), as shown on the previous slide. All trucks were EURO VI diesel engines (VI-a, VI-b and VI-c).
- Four DAF XF and CF vehicles were equipped with a more limited measurement system that only logged vehicle information from the CAN bus, but no physical measurements were conducted at the tailpipe. Within this CATALYST iVRI work package initially the five vehicles that were extensively logged were used in the analysis; if required the data from the remaining four vehicles can be processed as additional dataset or comparison set in a future study.



One of the outfitted trucks with the extensive SEMS measurement system



SEMS sensors welded in the vehicle's exhaust

Background on transport operations of data collected

6 transport companies participated, supplying 9 vehicles to the Integrator CTT project, having collected real operational data during their regular work in Floriculture and Container transportation

Floriculture transport



- Origins and destinations often at greenports such as Aalsmeer, Naaldwijk, Bleiswijk, Herongen
- Temperature-controlled, rigid trailers
- Relatively lighter gross combination weights (GCW)

Floriculture transport



**VAN DER SLOT
TRANSPORT**

Container transport



- Origins and destinations often at deep-sea terminals and inland terminals such as Port of Rotterdam, Venlo
- Container chassis
- Relatively higher GCW

Container transport



Overbeek
Container specialist



Typical fuel consumption for heavy-duty vehicles

In the Netherlands, we see ranges of heavy-duty vehicle fuel consumption of 0.3 l to 0.9 l of diesel fuel per km, depending on road type and application, translating to CO_2 emissions of approximately 780 to 2440 g of CO_2 per km

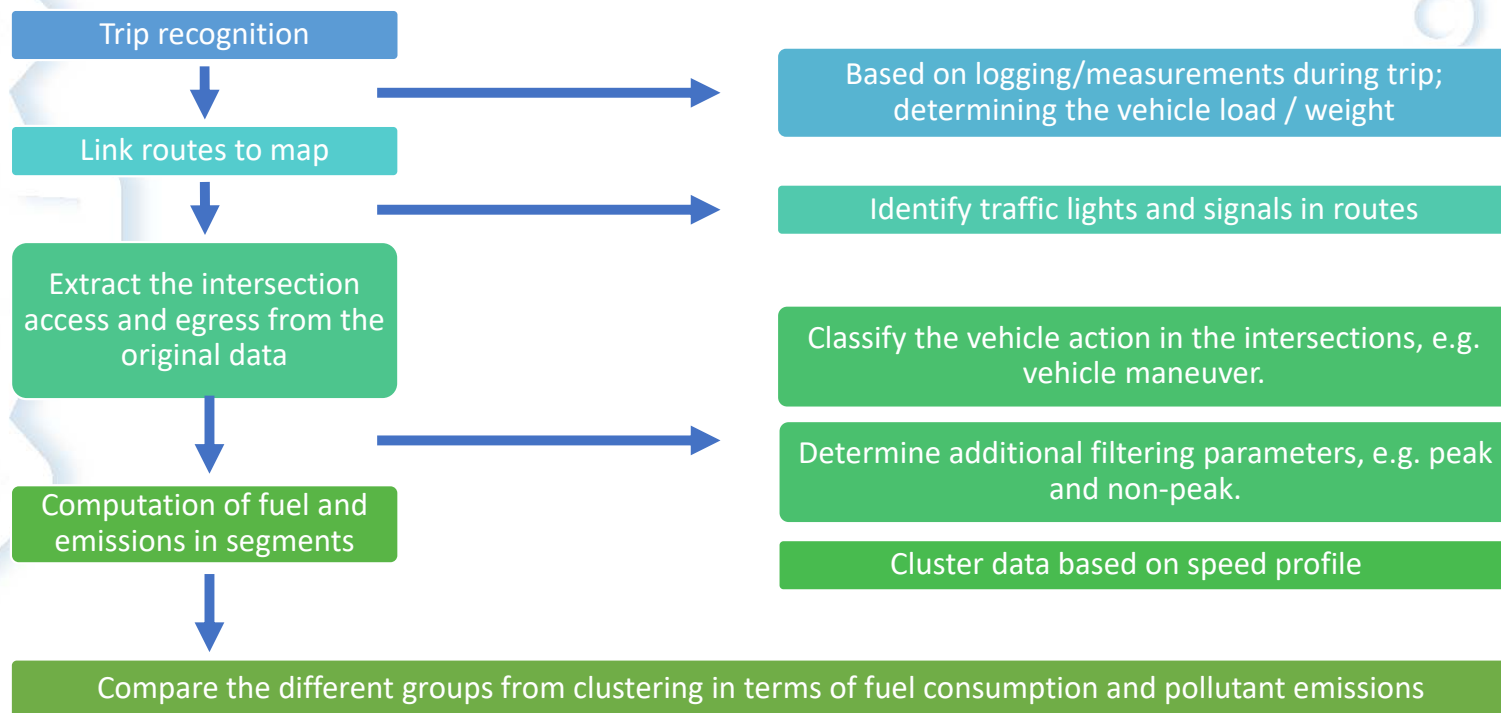
- Within the transport sector, as a general rule-of-thumb, people expect heavy-duty trucks to consume on average 1 l of diesel for 3 kilometres driven, or approximately 33 l per 100 km.
- Todts (2015) quotes an average European diesel consumption for heavy-duty trucks of 35 l / 100km, or 0.35 l per kilometer. At 2.606kg per liter, this translates to 912 grams of CO_2 per kilometer on average.
- Previous research has indicated that heavy-duty trucks in the Netherlands emit on average 768 grams of CO_2 on motorways, for a fuel consumption of 29 l per 100 km. For 2020, the previous study has estimated the heavy-duty fuel consumption to be somewhere between 0.30 l per km on motorways up to almost 1 l of diesel per km in congested urban areas (Ligterink et al., 2016)

Heavy Duty Vehicles	2015 - CO_2 (g / km)	2020 estimated – CO_2 (g / km)	2020 calculated – diesel NL (l / km)
Road type			
Urban congested	2356	2441	0.94
Urban normal	1542	1540	0.59
Urban free flow	1149	1105	0.42
Rural	994	1028	0.39
Motorway average	768	787	0.30

*CO2 emission and diesel fuel consumption in the Netherlands
Table adapted from Ligterink et al. (2016)*

Processing pipeline: from raw measurements to results

Overview of the total processing pipeline – the next slides go into detail about the steps in this pipeline



Processing the dataset: trip recognition

Based on SEMS data and map matching

- SEMS logs data at 1Hz, including CAN data, GPS traces and physically measured pollutant emissions
- All of GPS traces are map-matched to the OpenStreetMap (OSM) networks, using the Open Source Route Machine (OSRM)
- Based on the node 'tags' (e.g. 'Traffic Light') it becomes possible to reproduce whether vehicles passed individual traffic lights.
- By reproducing the trajectories at access, traversing and egressing at intersection(s) it becomes possible to determine whether the vehicle needed to stop.



Instrumentation of SEMS measurement system in one of the trucks

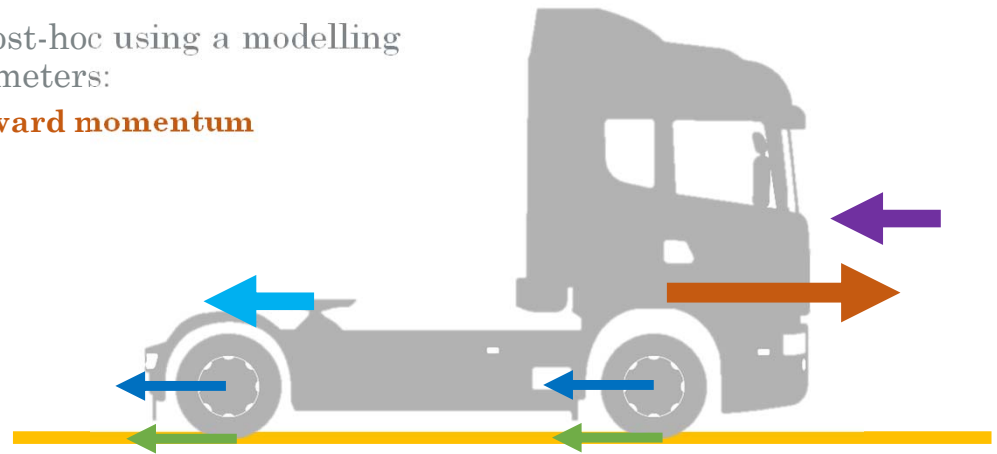
Determining the vehicle weights (1)

Proxied by analyzing the vehicle data

Vehicle weights are, of obvious reasons, an influencing factor for the fuel consumption and emissions of trucks. However the vehicle weights were not directly measured or logged during the Integrator Connected Truck Trial project. However, considering the research question of the present study we need to approximate the vehicle weights.

Therefore, we have estimated the vehicle weights post-hoc using a modelling approach employing the following information/parameters:

- **Engine information (torque and RPM) as forward momentum**
- **Mass of the trailer and payload**
- **Friction of the wheels**
- **Wind resistance and air drag**
- **Brake force**
- **Slope of the road**



Determining the vehicle weights (2)

Proxied by analyzing the vehicle data

Under these assumptions the mass of the vehicle combination (tractor + trailer + payload, also known as Gross Combination Weight GCW) was determined:

- At a speed of 50 km/h and slower, the air drag is assumed to be negligible
- The rolling friction force is assumed to be constant
- All measurements in which the brake pedal was activated are disregarded
- Slopes of the road in the Netherlands are very limited, by combining all measurements within a vehicle trip the effect of a slope is assumed to be averaged out.

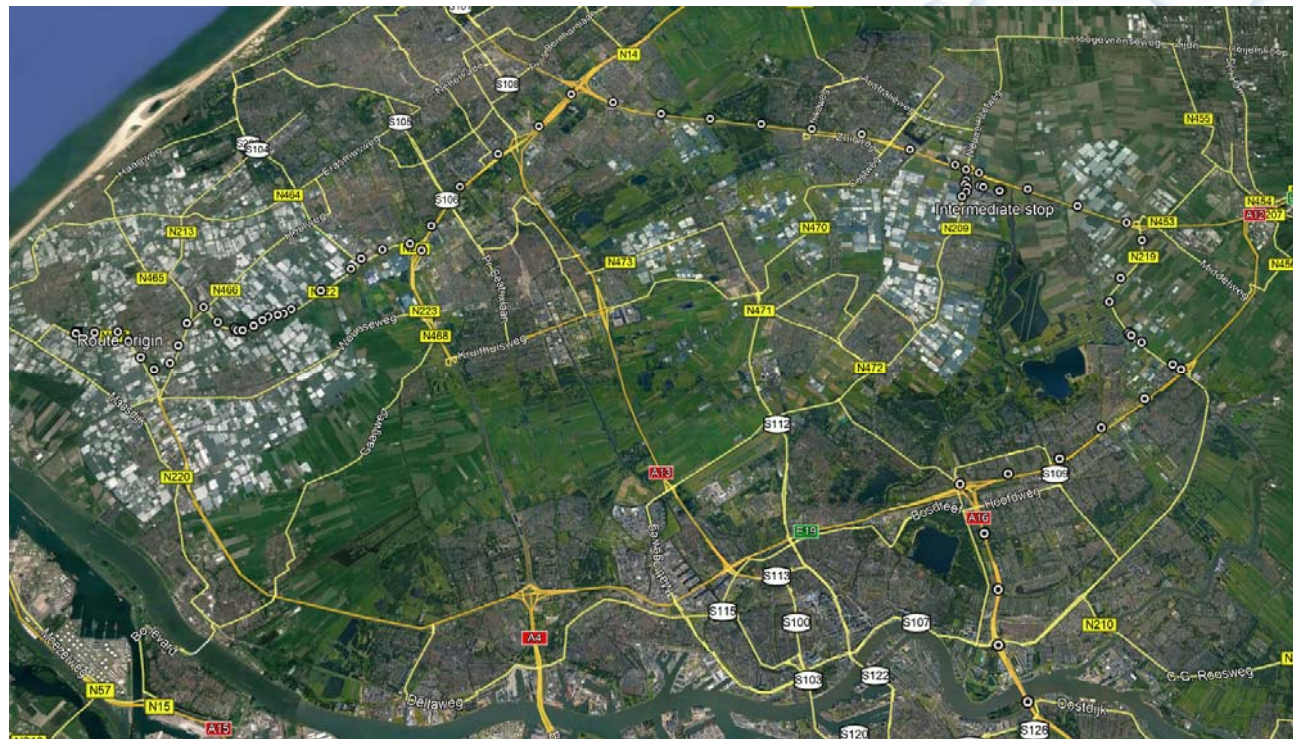
By applying the assumptions and analyzing the instantaneous RPM values (number of crankshaft rotations per minute), vehicle accelerations and by relating this data to the engine reference torque (from the vehicle specifications) the total vehicle mass is approximated.

Note; this analysis is indicative only, collecting and storing the 'real' vehicle loads is advised for future research. However the results are assumed to be good enough to split the dataset into lighter and heavier vehicles for subsequent analyses and investigation of various scenarios.

Example of the logging and processing of an individual trip in the province of Zuid Holland – raw GPS data

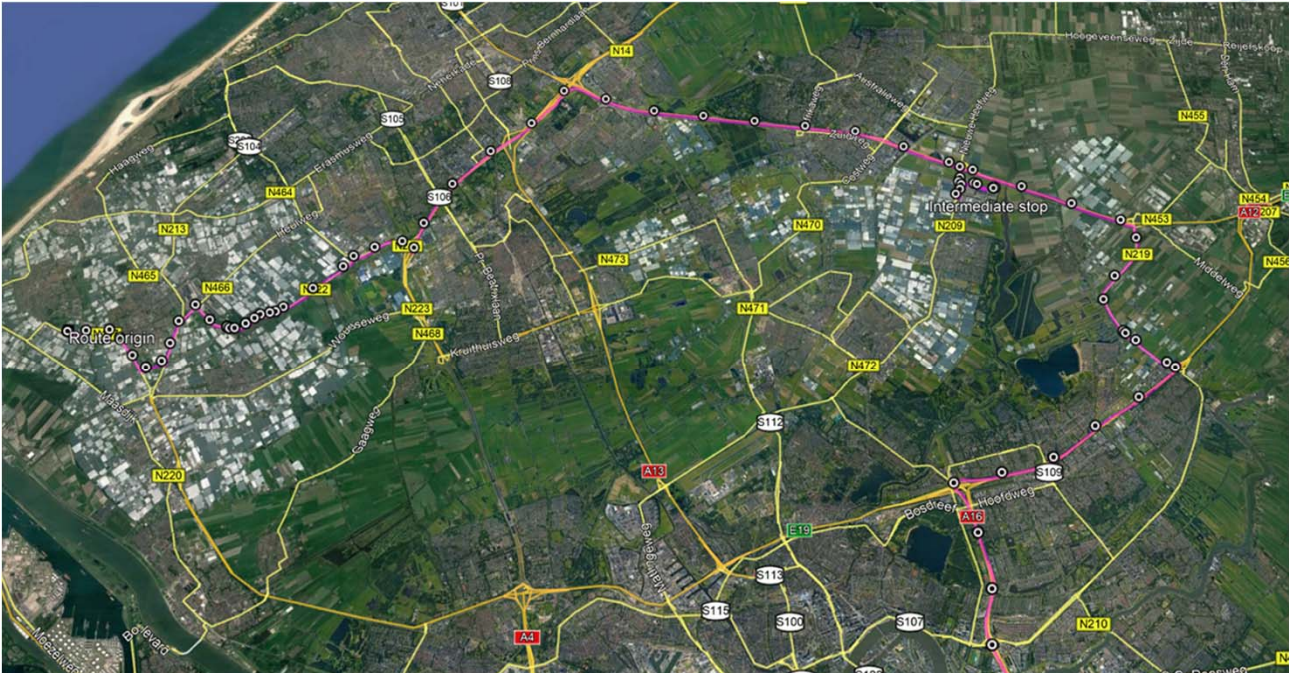
Example: a Getru trip, with individual GPS points at a 15 sec. interval.

Note: SEMS logs at 1Hz however Google Earth is not able to display all the GPS points

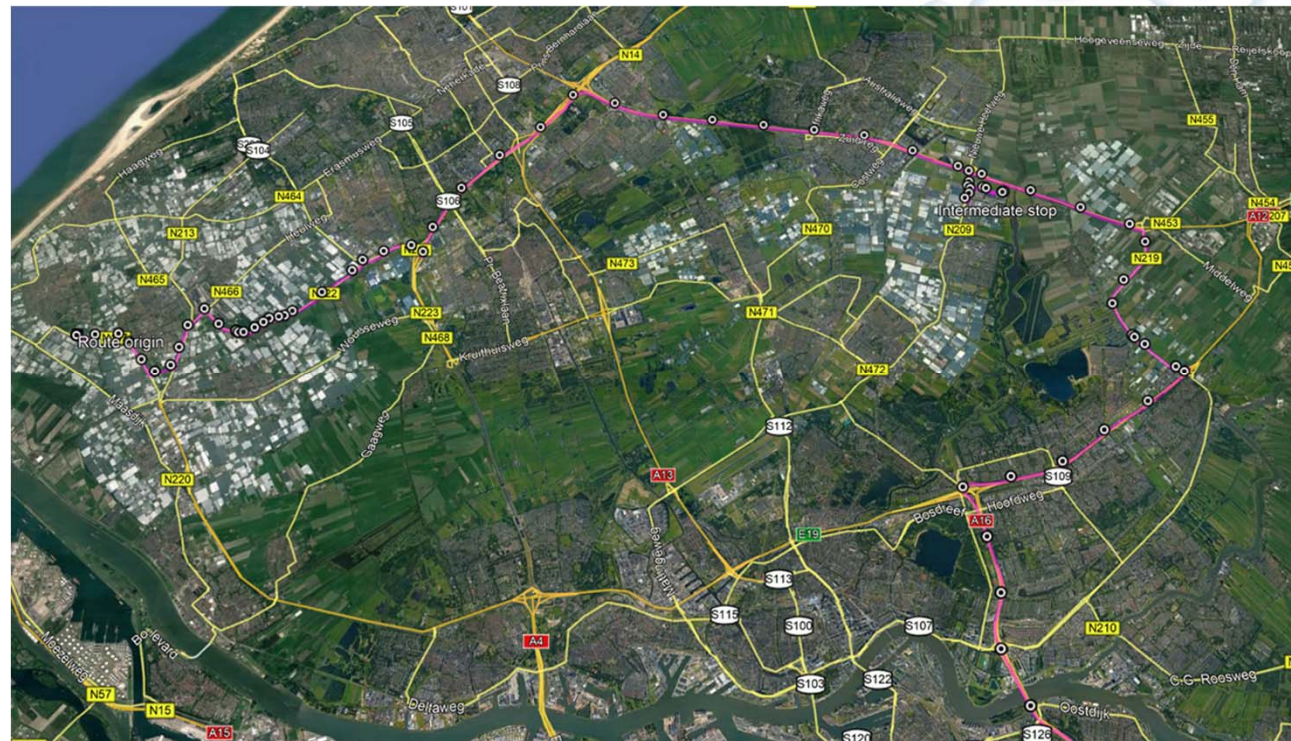


Example of the logging and processing of an individual trip in the province of Zuid Holland – trip recognition

Using OpenStreetMap and the Open Source Routing Machine (OSRM), the GPS points are MapMatched as a full trajectory



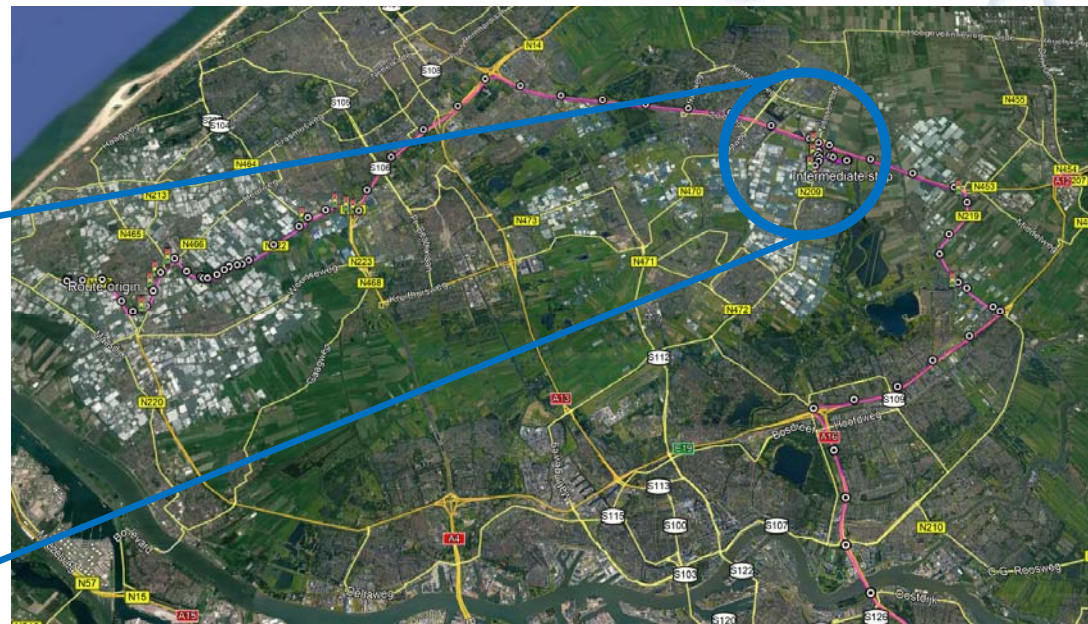
Using OpenStreetMap Source Routing Method GPS points are Matched to trajectory



Example of the logging and processing of an individual trip in the province of Zuid Holland – identify traffic lights

Based on the OSM intersection tags the individual signalized intersections are singled out.

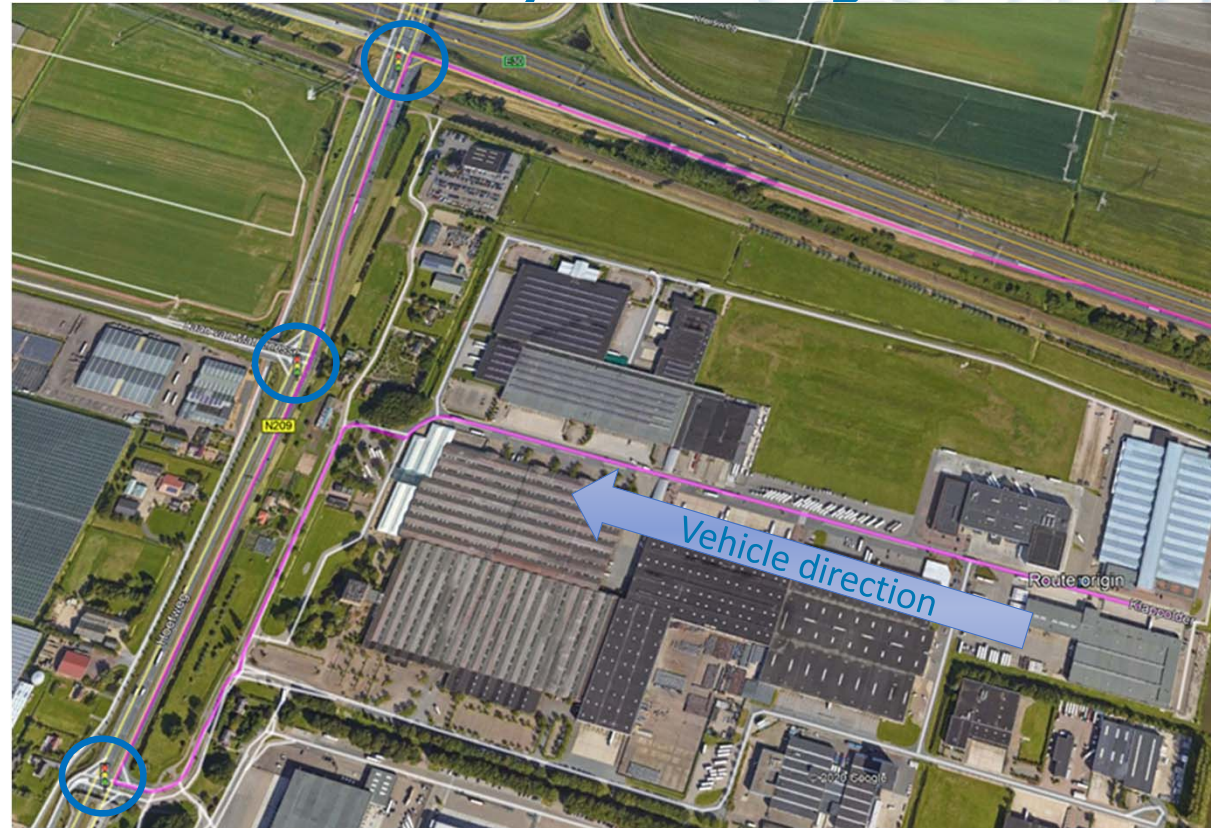
(Look for the very small traffic light symbols on the map)



Example of the logging and processing of an individual trip in the province of Zuid Holland – identify traffic lights

A Getru trip: a detailed plot of part of the trajectory

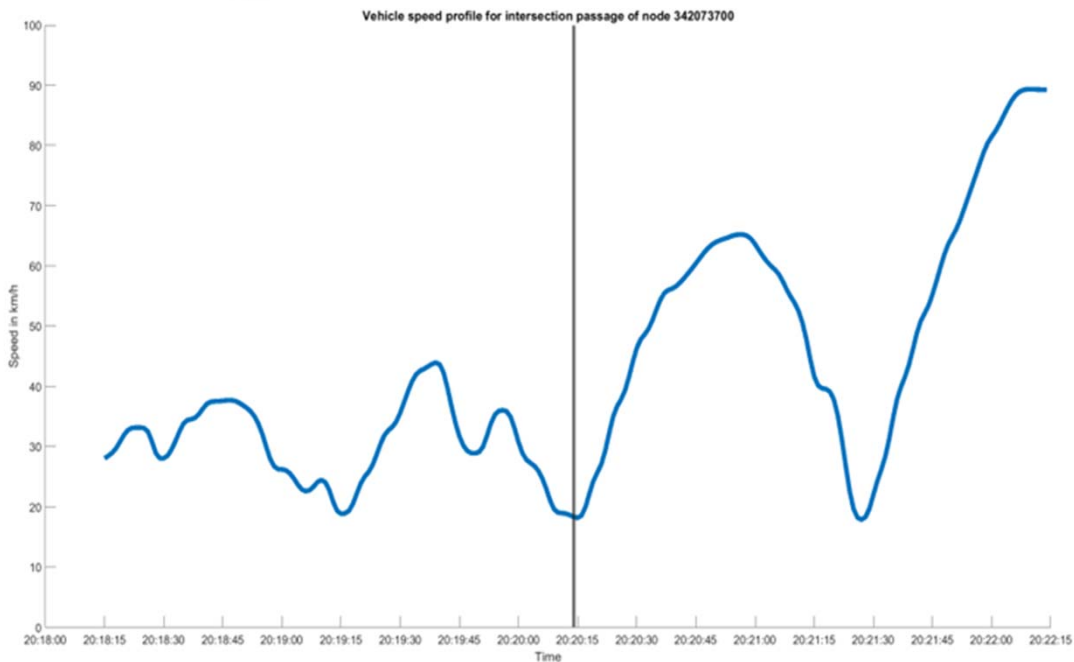
Notice how the vehicle passes three traffic lights on its way from the N209 highway to the A12 motorway



Example of the logging and processing of an individual trip in the province of Zuid Holland – with speed profiles

A detailed plot of part of the trajectory

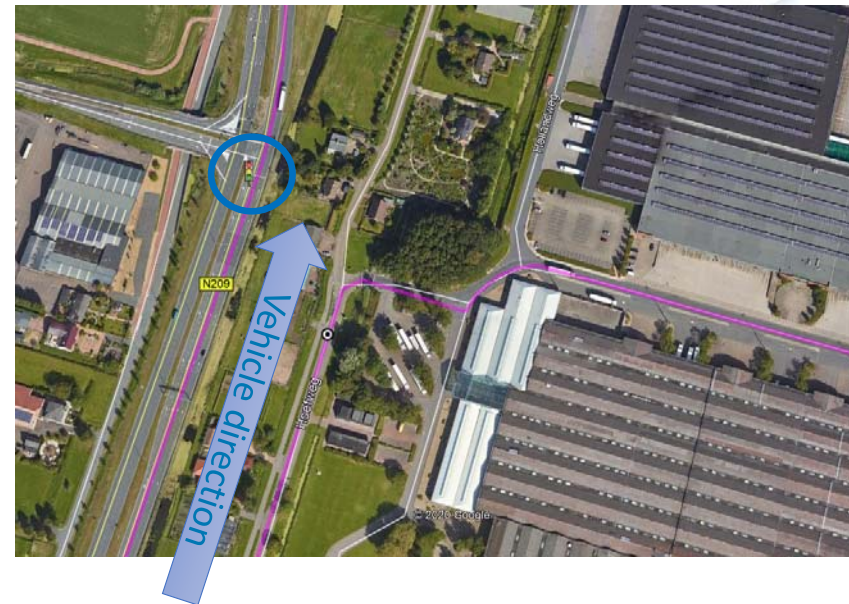
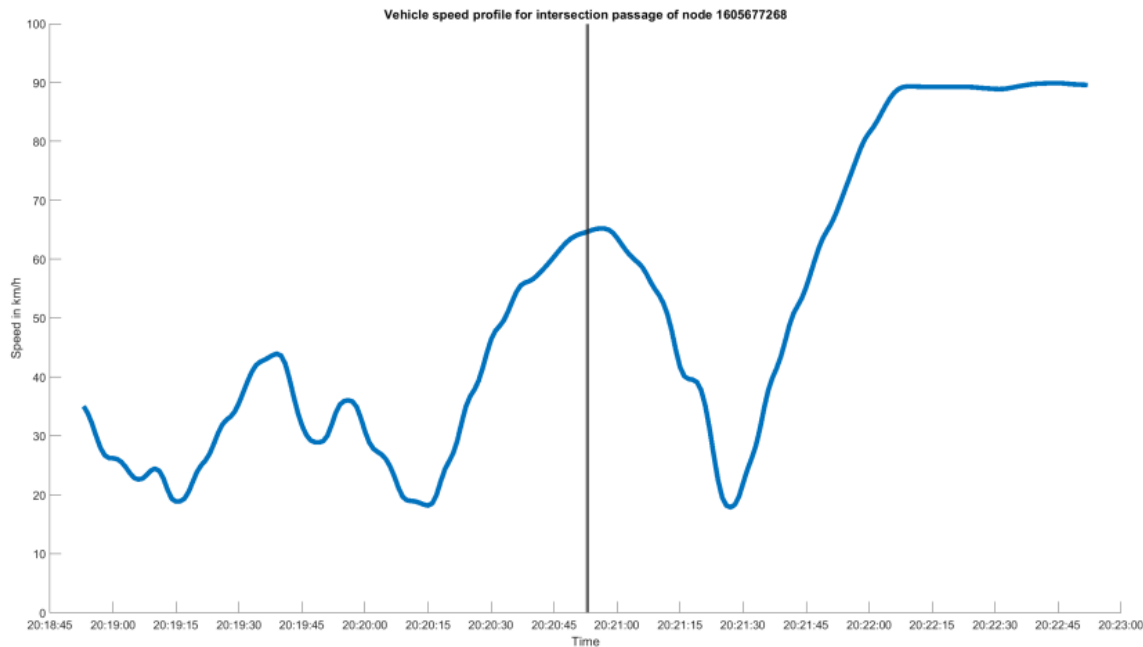
... enriched with the vehicle speed profile for passing the first intersection



Example of the logging and processing of an individual trip in the province of Zuid Holland – with speed profiles

A detailed plot of part of the trajectory

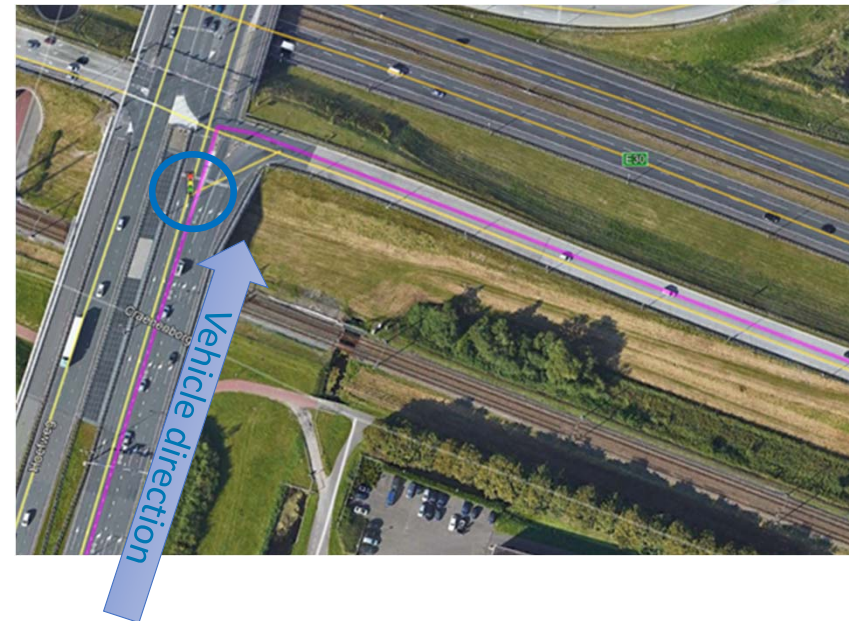
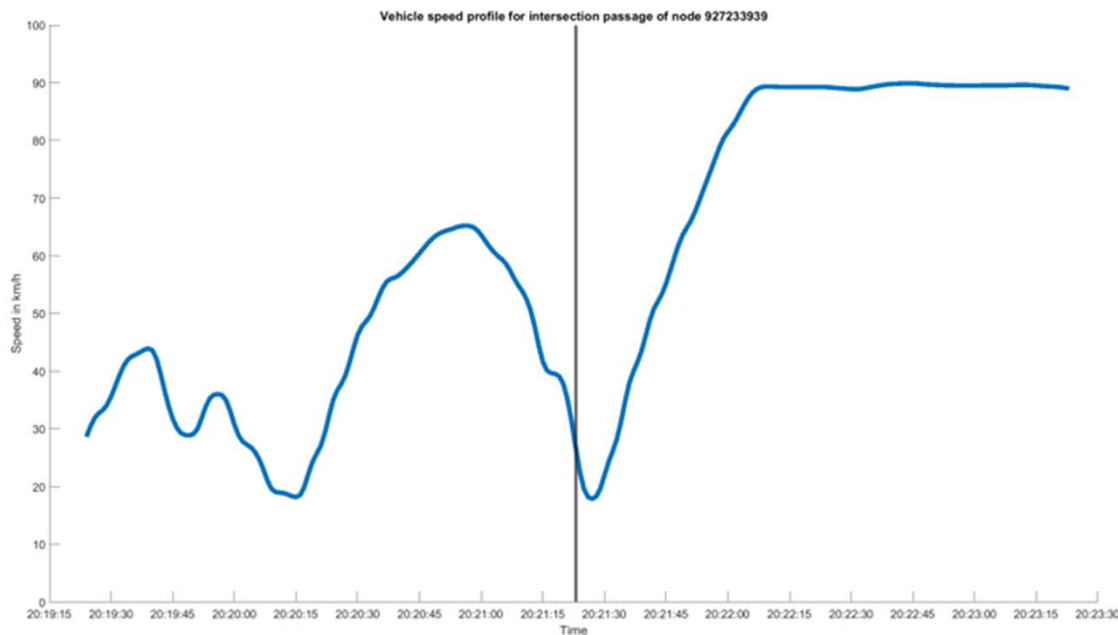
... enriched with the vehicle speed profile for passing the second intersection



Example of the logging and processing of an individual trip in the province of Zuid Holland – with speed profiles

A detailed plot of part of the trajectory

... enriched with the vehicle speed profile for passing the third intersection



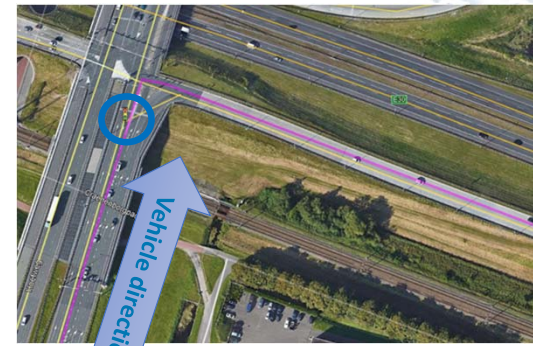
The vehicle turning speed correlated with the corner radii



Right turn



Straight

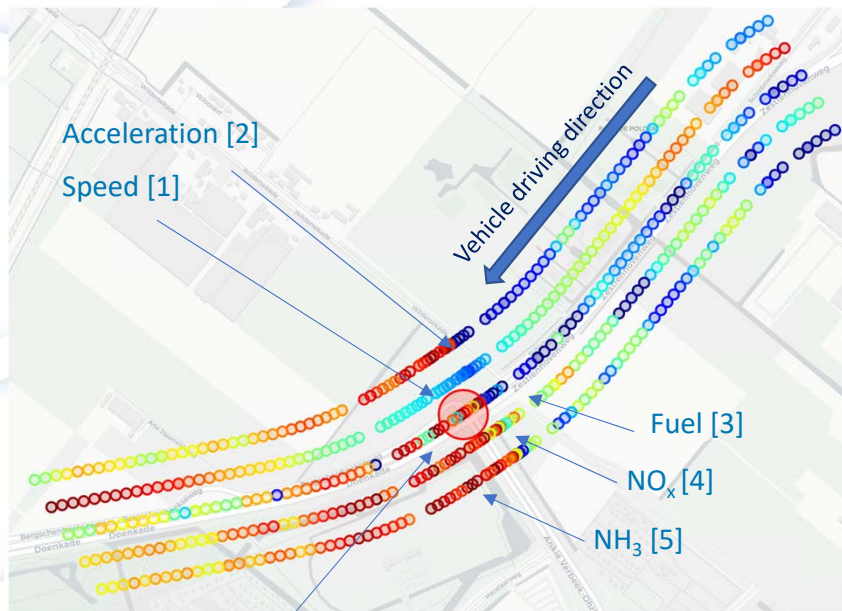


Right turn

- Regardless of stopping or not at the traffic light, the maneuver at the intersection, and the type of curve has a great impact on the speed behavior i.e., the smaller the radius the slower the speed. Then, the classification of the direction followed in the intersection is needed.
- Within the data clustering only straight intersection passages were considered.

Example showing the instantaneous and synchronized data collection for a vehicle traversing an intersection

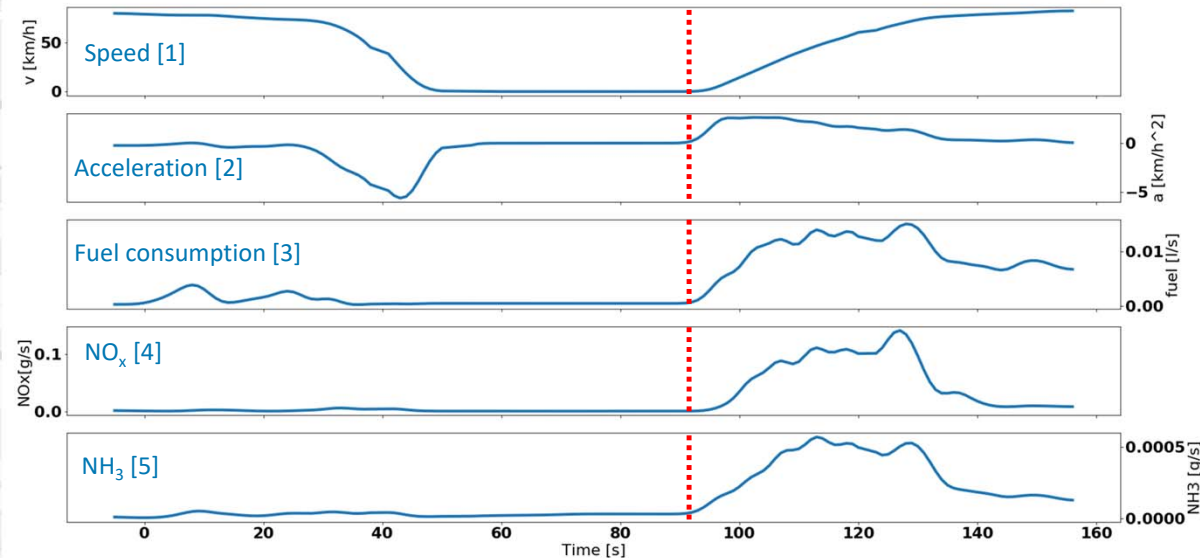
Time-series data collected using SEMS at 1Hz of a single trip when traversing an intersection (red circle and line)



Intersection location



The color indicates the relative value of each quantity, colder colors being smaller and hot colors larger.



HEAVY DUTY TRANSPORT LIVING LAB

Enrichment of VRI passages

Parameterization and classification used to enrich data for VRI passages



Selection of trips
(all trips in NL)

Origin



Vehicle stop defined as the
occurrence of at least one
speed value < 2 km/h

Adding additional data
from OpenStreetMap (road
class and maximum speed)

Desti-
nation

Access area | 100 m

Egress area | 100 m

for detection of maneuvers and additional metadata (maneuvers, traffic lights)

Region up to the intersection area | 1000 m

for classification and determining the scenario

2000 m – total analysis area

(1000 m before and 1000 m after intersection)

Enrichment of VRI passages

Visualization

A vehicle westbound on the N218 passes a signalized intersection.

Access



Egress



Analysis area



4 | Scenario definition, sampling and data processing

This section introduces the scenarios for which the (clustering) analyses are performed

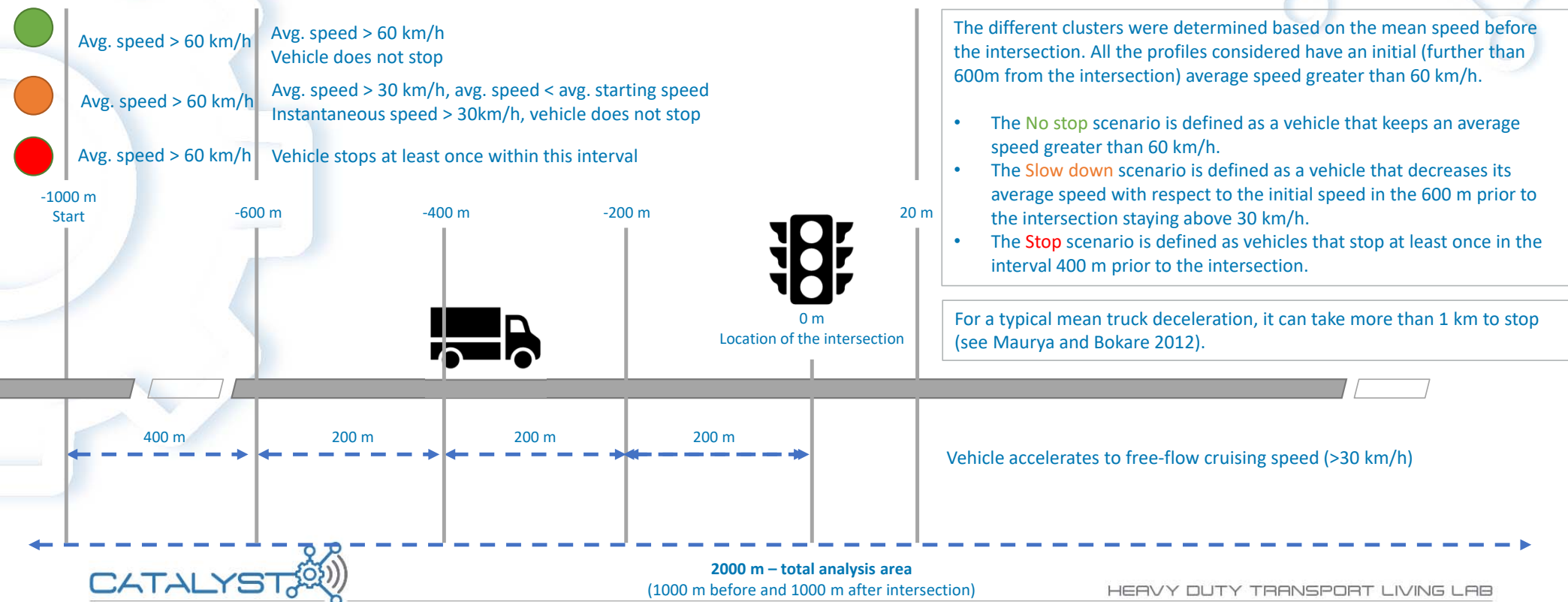
Scenario definition by PZH: 3 driving scenarios identified for heavy-duty vehicles traversing an intersection

PZH has delivered 3 scenarios that are driving situations that could occur for heavy-duty vehicles and that PZH desires to be investigated. The identified driving scenarios are referred to as clusters within the subsequent analysis, as we have used the scenarios to obtain clusters in the data analysis.

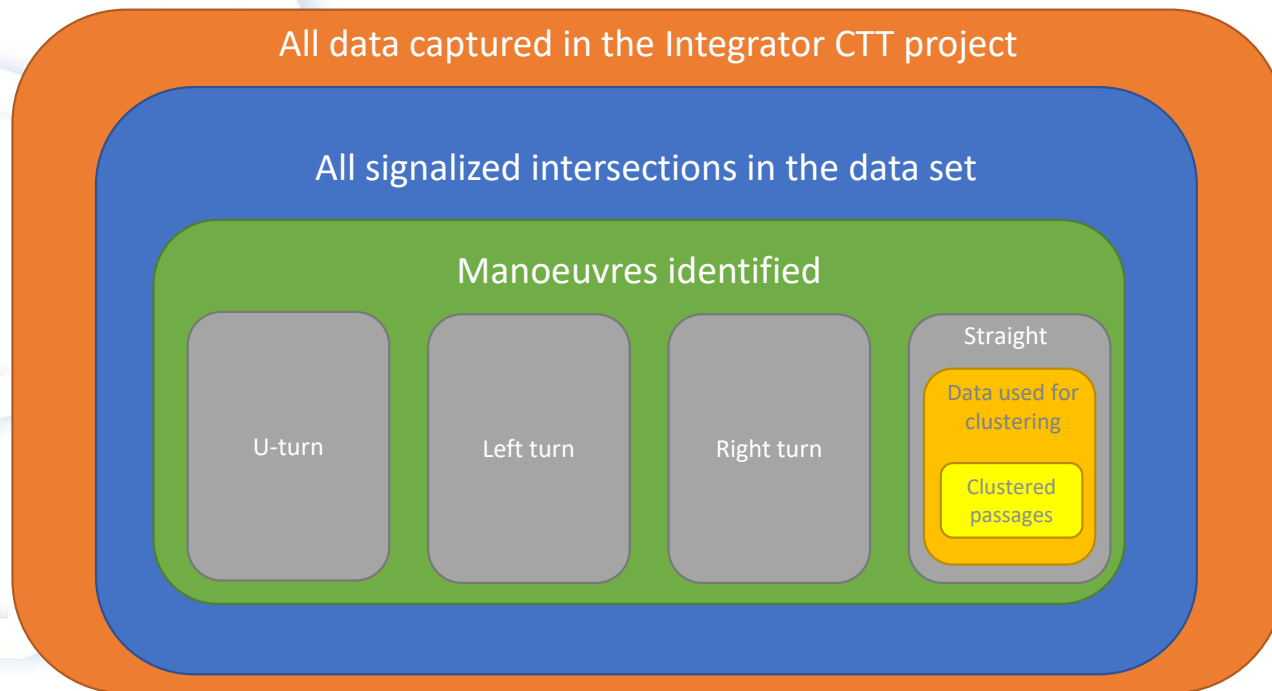
	Driving scenario (cluster)	Scenario description
	No Stop	The truck passes the traffic light without stopping nor slowing down. The truck can maintain its cruising/free flow speed while approaching and subsequently traversing the intersection.
	Slow down	The truck passes the traffic light slowing down significantly. The truck accelerates prior or after the intersection to reach free-flow cruising speed again.
	Stop	The truck stops at or near the intersection crossing line. The truck has to accelerate from standstill.

For some of the analyses, the above scenarios are split into weight categories for heavier and lighter trucks, to arrive at a total of six scenarios (that is, clusters).

Clusters were determined from the provided scenarios based on the speed profiles of intersection crossings



Sampling strategy: going from vehicle trajectories to filtering for relevant intersection passages (1)



Only straight maneuvers have been included for the final analysis. This leads to exclusion of about 2/3 of the samples from the original dataset of 11087, remaining only 4972 samples.

Over the 4972, the clustering based on the speed profile is done, and only 902 samples are found in the defined clusters.

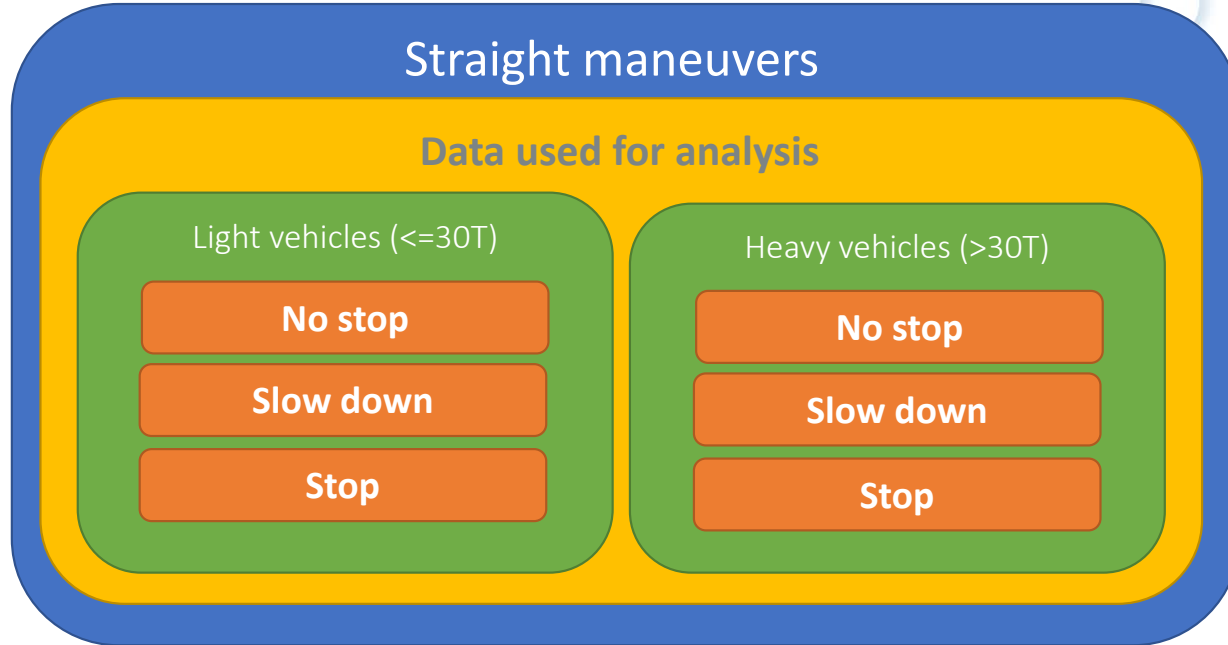
This provides much more reliable results. Maneuvers that are not straight have a direct correlation with the speed profiles that would affect the results. Furthermore, the clustering needs to be strict to perform fair comparisons.

Cluster	Number of signalized intersection passages
No stop	378
Slow down	349
Stop	175
Total	902

Sampling strategy: going from vehicle trajectories to filtering for relevant intersection passages (2)

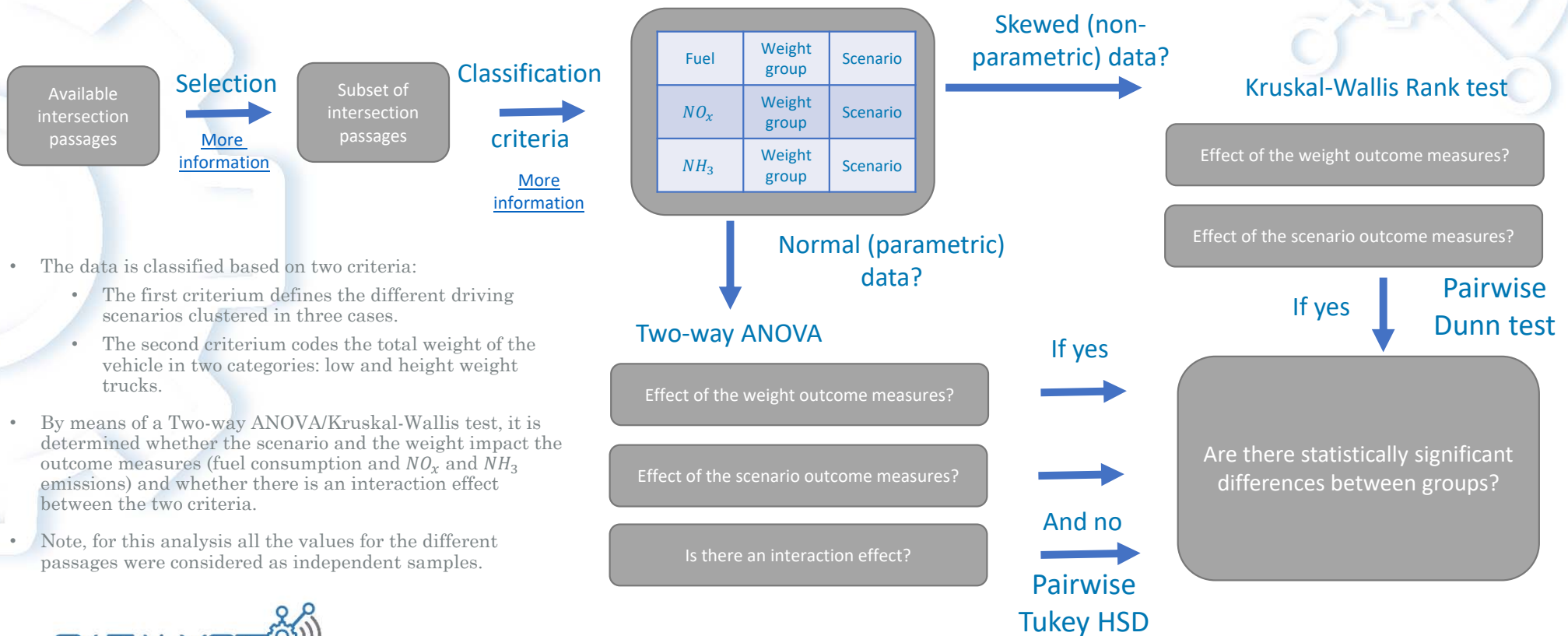
Subsequently the dataset that remains is (again) split in multiple clusters, the definition of these clusters have been discussed and agreed upon with the Province of Zuid Holland.

Due to the frequent splitting of the dataset, it is expected that the sample sizes per cluster will be limited. Think of it as peeling an onion; you will quickly see that the onion is strongly decreasing in size. Even with a dataset as large as the Integrator CTT project.



Statistical analysis flowchart

After clustering analysis, statistical analysis is performed using the following global procedure



- The data is classified based on two criteria:
 - The first criterium defines the different driving scenarios clustered in three cases.
 - The second criterium codes the total weight of the vehicle in two categories: low and height weight trucks.
- By means of a Two-way ANOVA/Kruskal-Wallis test, it is determined whether the scenario and the weight impact the outcome measures (fuel consumption and NO_x and NH_3 emissions) and whether there is an interaction effect between the two criteria.
- Note, for this analysis all the values for the different passages were considered as independent samples.

Data selection: unreliable data is discarded

Motivation for further sample size reduction

To proceed with the analysis, the data must fulfil certain properties. In this process the total amount of samples is reduced (filtered) for the sake of keeping the dataset homogeneous, in order to improve the validity and reliability of the results.

From all the intersections in which the vehicle executes a straight-driving maneuver, further samples are discarded based on the following criteria:

- **Too short trajectory before or after the intersection.** The intersection can be located near the origin or destination in which cases the segments of the trajectory before or after the intersection are too short to allow the analysis.
- **Unreliable measurements.** For exhaust gas temperatures (EGT) lower than 200 °C the measurements of NO_x and NH_3 are not reliable. For this reason these segments are discarded, reducing the sample size.

5 | Descriptive statistics and cluster analysis

This section provides descriptive statistics of the processed dataset and cluster analysis results.

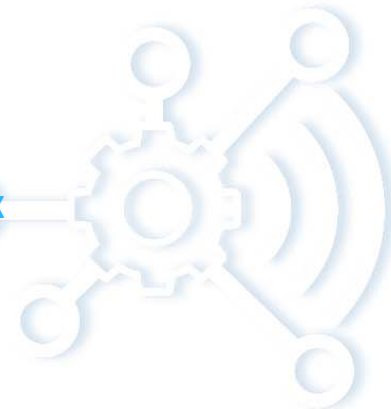
Some statistics for the full non-filtered dataset

Based on 5 vehicles with on-line (extensive) SEMS measurement platform

Year	Weeknumber	Number of routes	Number of routes in PZH	Number of trips	Number of trips in PZH	Mileage in kilometers	Mileage in PZH	# Intersection passages	# Intersection passages in PZH
2019	37	35	26	195	73	4953	4053	423	315
2019	38	45	23	275	93	5215	4046	485	369
2019	39	42	27	247	89	6399	4928	473	327
2019	40	45	26	270	98	5208	4329	525	383
2019	41	53	24	284	113	4355	3725	535	425
2019	42	55	33	220	88	3981	3322	471	367
2019	43	46	26	227	96	3859	3139	552	430
2019	44	34	21	171	68	4406	3644	363	266
2019	45	39	17	150	48	3274	2496	292	163
2019	46	39	21	191	66	4507	3669	404	303
2019	47	43	23	199	84	4114	3125	589	413
2019	48	38	28	193	69	5336	4566	387	301
2019	49	38	22	179	62	5926	4987	363	182
2019	50	37	24	290	94	6166	5072	531	367
2019	51	19	14	140	54	3540	3123	368	276
2019	52	7	5	54	15	1238	1069	160	55
2020	1	16	13	104	50	3784	3626	284	233
2020	2	44	30	257	86	7086	5935	543	345
2020	3	31	17	201	65	4089	3264	401	294
2020	4	34	22	213	75	6520	5446	450	273
2020	5	25	21	222	98	6099	4339	504	401
2020	6	41	25	241	90	4125	3125	528	402
2020	7	33	22	203	72	3733	2959	456	322
2020	8	35	26	203	95	2711	2508	498	456
2020	9	24	21	147	69	2863	2422	502	345
		898	557	5076	1910	113485	92918	11087	8013

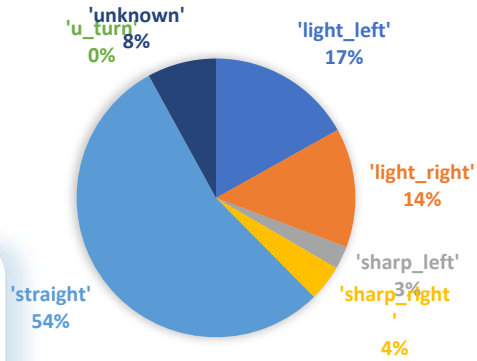
Some statistics of the full non-filtered dataset (1)

Whole of the Netherlands



This graph shows the distribution of maneuvers at signalized intersections.

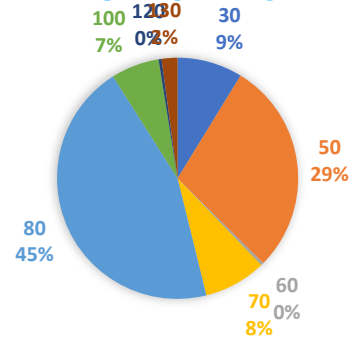
REVEALED MANOEUVRES



This graph shows the road types (in speed categories) for which signalized intersections were traversed.

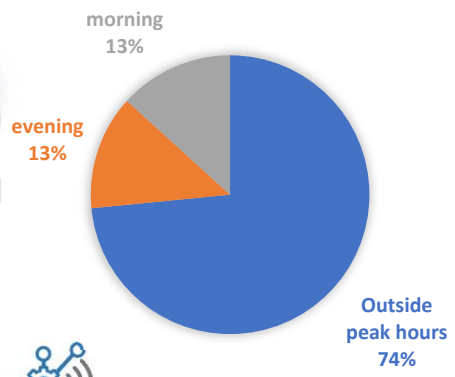
DISTRIBUTION ACROSS MAX

ROAD SPEEDS



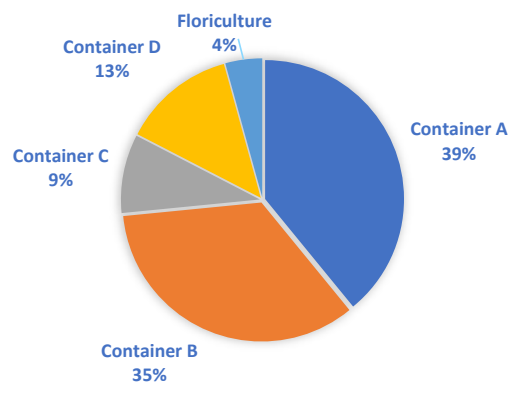
This graph shows the percentages of intersection passages in and outside peak hours

PASSAGES WITHIN PEAK HOURS



This graphs shows the intersection passages per vehicle and per logistical category

DISTRIBUTIONS ACROSS VEHICLES



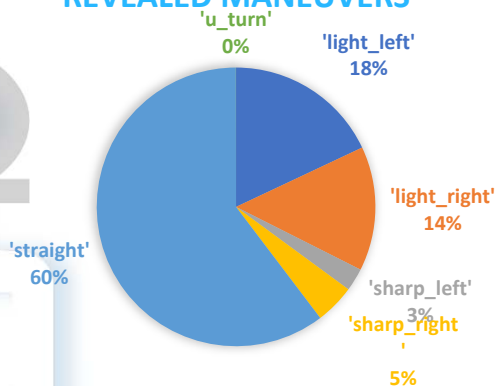
This graph refers to the individual vehicles in the sample. Almost all the data stems from 4 of the container trucks, with only a limited amount of data from one of the floriculture trucks.

Note, the dataset allows multiple different statistics and cross sections, the graph here are some examples.

Some statistics of the full non-filtered dataset (2)

Province of Zuid Holland

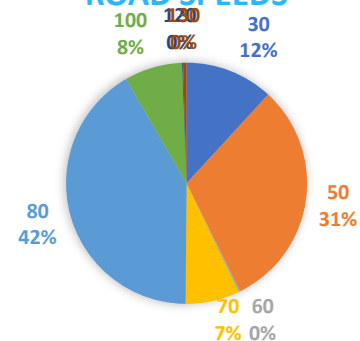
REVEALED MANEUVERS



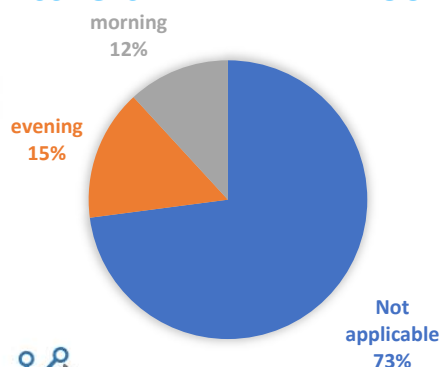
This graph shows the road types (in speed categories) for which signalized intersections were traversed.

DISTRIBUTION ACROSS MAX

ROAD SPEEDS

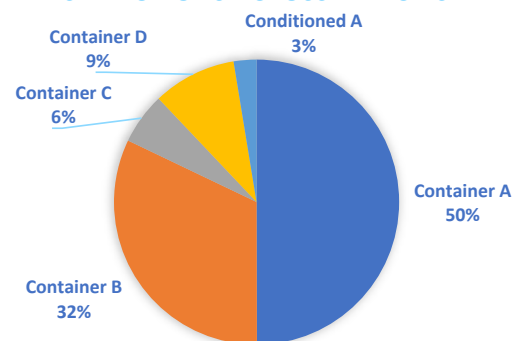


PASSAGES WITHIN PEAK HOURS



This graph shows the intersection passages per vehicle and per logistical category

DISTRIBUTIONS ACROSS VEHICLES



Note, the dataset allows multiple different statistics and cross sections, the graph here are some examples.

Estimated vehicle weights (1)

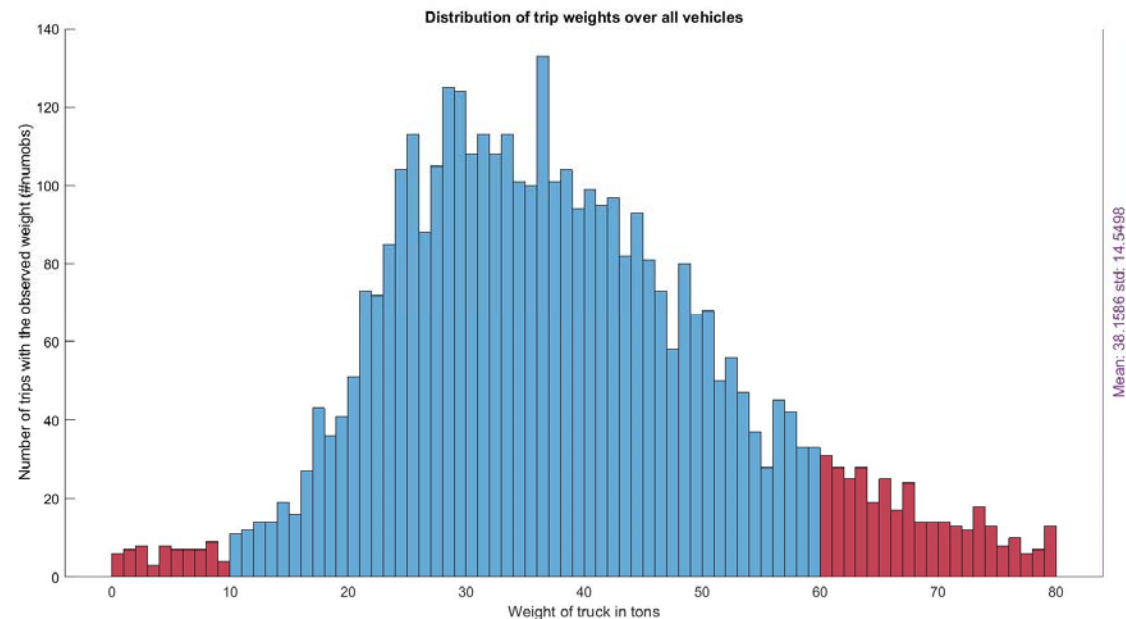
For all vehicles in the unfiltered dataset

Based on measured data and vehicle parameters the total weight of the tractor, trailer and payload have been estimated.

The figure on the right depicts a histogram of the weights (in metric tons) that were deduced from the individual trips. For each intersection passage the estimated weight is subsequently considered for the data clustering.

The mean vehicle weight is 38 tons and has a standard deviation of 14,5 tons.

Within the histogram the both ends (<10 & >60) have been marked red, these estimated values are assumed to be questionable (a tractor with trailer but without payload is already well over 10 tons, and the maximum weight limit for LZVs is 60 tons in the Netherlands) – these (questionable) numbers result from the quantitative estimation, for instance when a vehicle has been driving downhill.



Estimated vehicle weights (2)

The vehicle weights for each specific vehicle in the dataset

For the individual vehicles in the dataset, the weight histograms have also been prepared, however these are not significantly different than the histogram for all vehicles. In the table below the mean weight and standard deviations are shown for all individual vehicles, moreover this table contains the load type of the vehicle.

Please note, within the data clustering of intersection passages we split the data for light and heavy trucks in 2 groups, with a split at 30 tons. The reasoning here is that a tractor with trailer but without payload is already well over 10 tons and the maximum weight for regular trucks is 50 tons and for LZVs is 60 tons in the Netherlands. 30 tons is therefore a logical split point, which fits well with earlier research, for instance Kuiper and Ligterink (2013) that showed 28.2 tons to be the Dutch average in 2013.

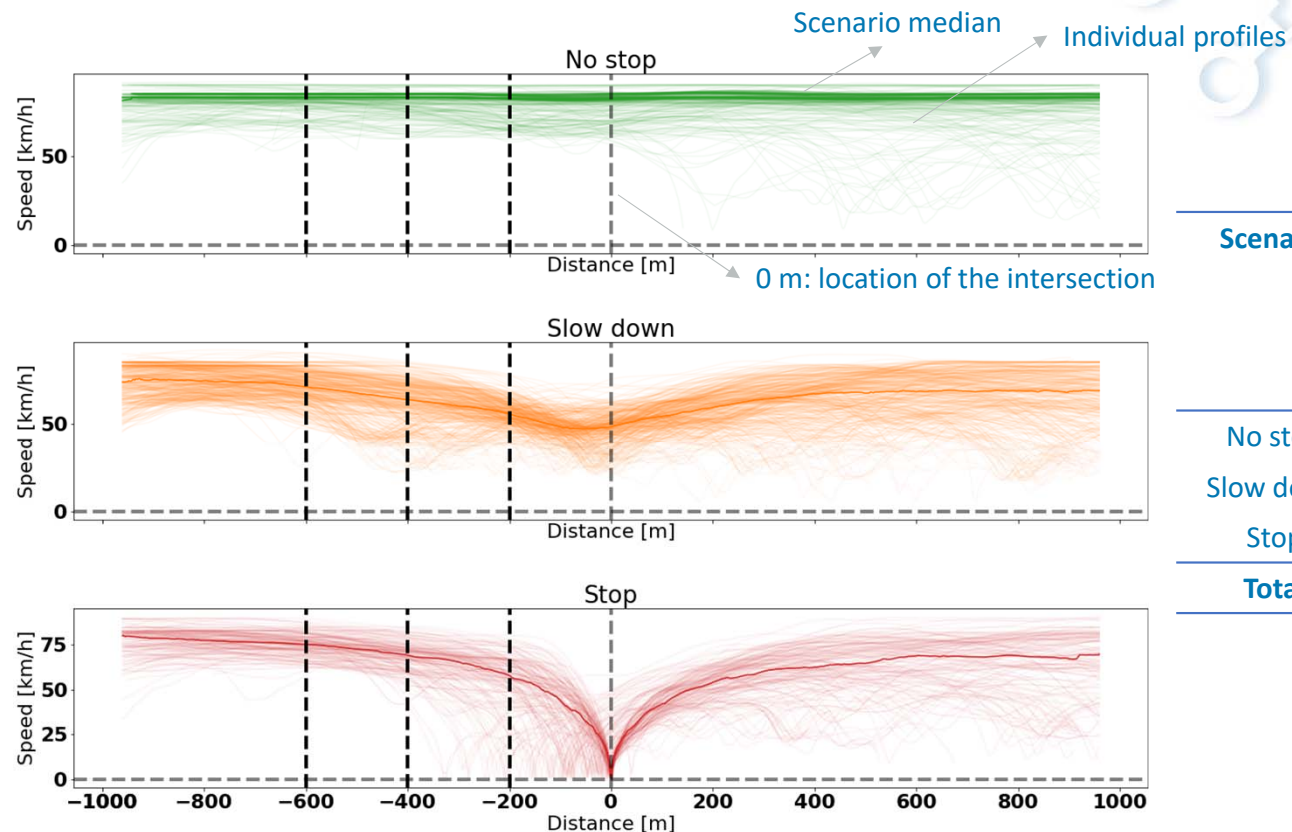
Our sample, thus, consists of comparatively heavy truck combinations with most individual trucks on average being heavier than the 30 tons split point.

Vehicle name	Load type	Mean weight in tons	Standard deviation of the weight in tons
Vehicle_1A	Container	35,1	13,5
Vehicle_1B	Container	40,7	14,7
Vehicle_2A	Container	39,5	14,7
Vehicle_2B	Container	38,4	15,1
Vehicle_3A	Floriculture	39,9	17,1
Sample mean	Both	38,2	14,5

Clustering: assigning every individual intersection passage to one of the driving scenarios

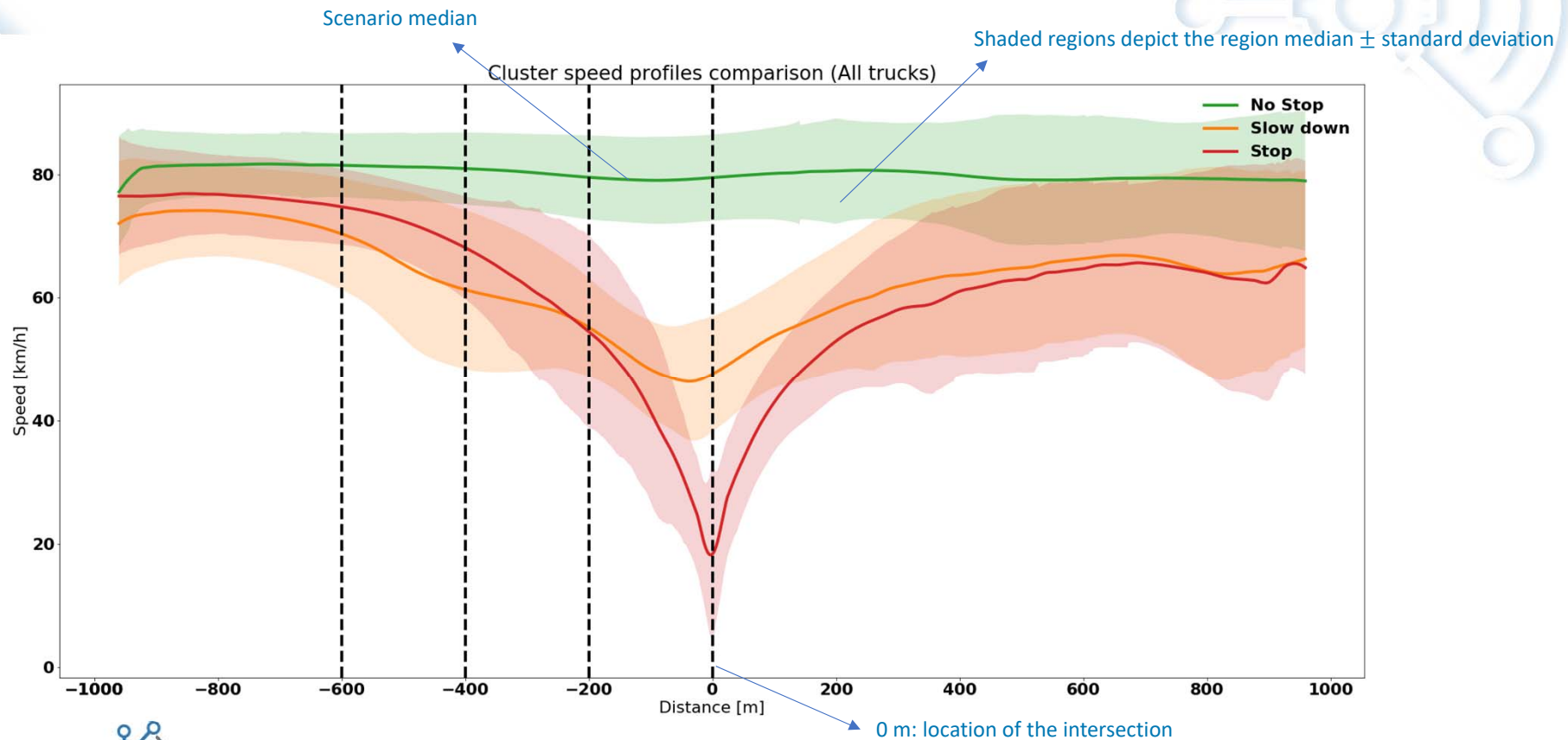
The thin (colored) lines all represent individual intersection passages. The denser line shows the median for that cluster.

Some interesting things may be observed: in the case of the Stop-cluster, quite some vehicles stop some distance before the intersection stop line, probably an indication of queues. Also, for all three clusters, while vehicles typically accelerate after traversing the intersection, some slow downs also occur, which may point to typical erratic acceleration and slowing down driving behaviour when clearing the (busy) egress area.



Scenario	Number of samples of signalized intersection passages
No stop	378
Slow down	349
Stop	175
Total	902

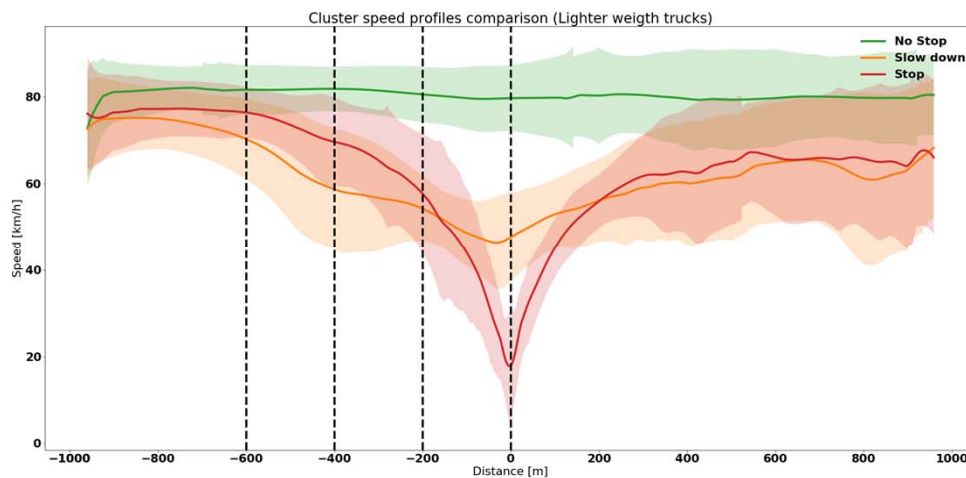
Cluster overview for all trucks in the final filtered sample



The 3 clusters may also be analyzed taking vehicle combination weight into account, for a total of 6 clusters

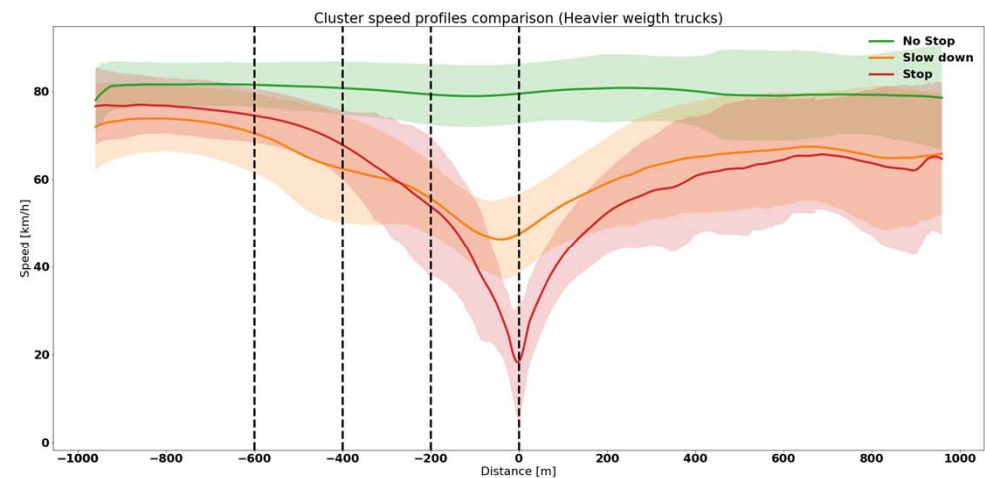
3 speed-profile based clusters for lighter vehicles and 3 clusters for heavier weight vehicles

Lighter weight trucks



Scenario	Number of passages
No stop	84
Slow down	98
Stop	31
Total	213

Heavier weight trucks



Scenario	Number of passages
No stop	291
Slow down	251
Stop	144
Total	686

6 | Results and interpretation

This section shows the results of the analysis for, the fuel consumption and NO_x and NH_3 emissions when traversing signalized intersections

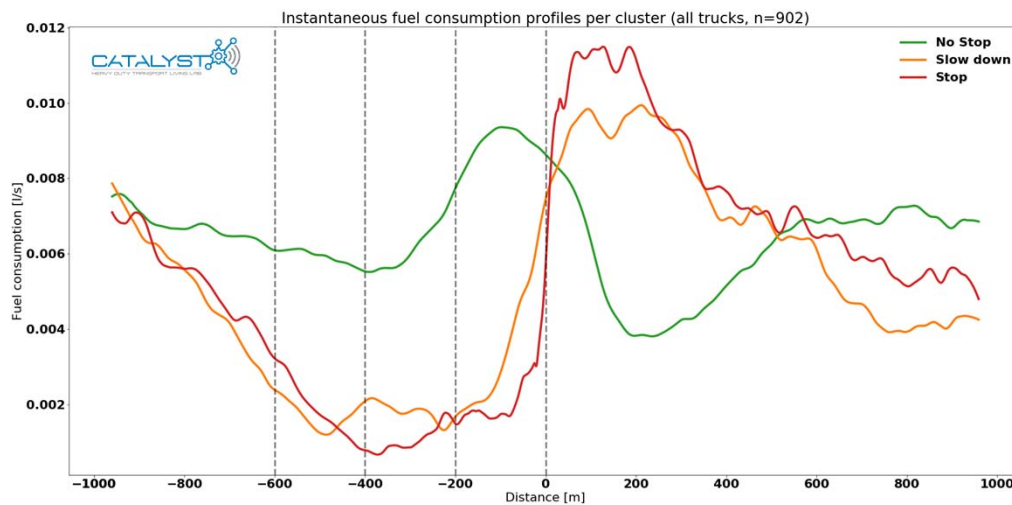
Interpreting and understanding fuel consumption savings

Full results and plots on the next slides

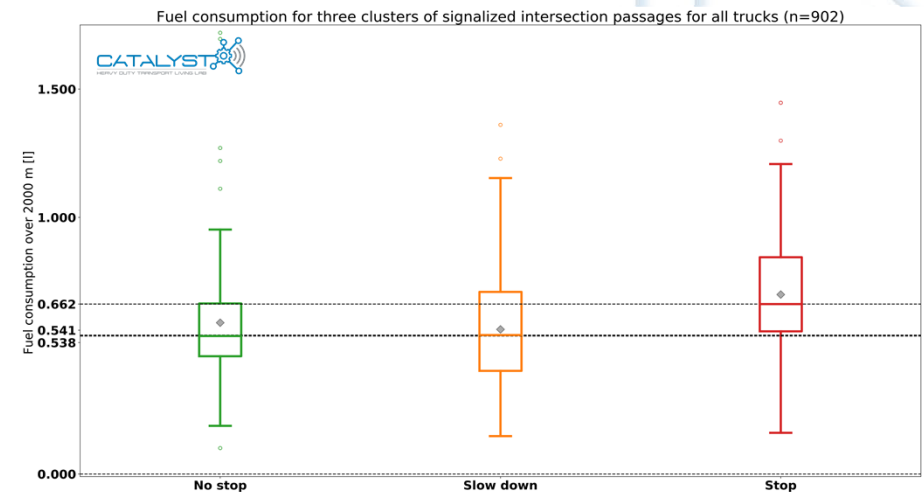
- This study determines the difference in fuel consumption between three different clusters while traversing signalized intersections: one in which the vehicle completely stops (**stop** cluster), one in which the vehicle does not stop (**no-stop** cluster) and a third one in which the vehicle decreased its speed (**slow down** cluster). The interpretation of the fuel consumption values in the intersections related to each cluster can be done comparing the speed and instantaneous fuel profiles.
- The median fuel consumption difference between the stop-cluster (0.662 l) and non-stop cluster (0.538 l) is 0.124 l, with significant differences of the means of these two clusters. At 2.618 kg CO_2 per liter of diesel, this translates to a median saving of 0.32 kg of CO_2 per avoided stop at the intersections in the dataset.
- It turns out that avoiding the complete stop, by slowing down from 80 km/h to 40 km/h is almost as efficient as the free-flow non-stop speed cluster, with a fuel saving of 0,120 l. Acknowledging the complexity of defining the clusters, the slow down cluster is considered as an intermediate case, and its fuel consumption value of 0.542 l supports it. The limited (non-significant) difference to the stop-cluster possibly results from the fact that slowed-down driving is actually more fuel efficient than driving at higher speeds (70-80 km/h) due to lower air resistance at lower speeds, effectively compensating for the fact that the truck still needed to accelerate after traversing the intersection.

Fuel consumption of heavy-duty trucks when traversing signalized intersections

Median saving of 0.12 l of fuel for the non-stopping scenario compared to the stopping scenario



Interpretation: as may be observed from the plots, the stop-cluster has a higher median fuel consumption (across the 2 km trajectory under analysis) than the other two clusters. Stopping uses an additional 0.12 l of fuel compared to the no-stop scenario. Or the other way around: not having to stop results in a median saving of 0.12 l of diesel and 0.32 kg of CO_2 compared to the stop-cluster. The stop-cluster results are significantly different from both the no-stop and slow-down clusters, as Tukey's post-hoc test shows.



Tukey's HSD post-hoc test for pair-wise comparison | fuel consumption, full sample

group1	group2	meandiff	p-adj	Lower	upper	reject
no stop	slow down	-0.0161	0.5893	-0.0552	0.0229	FALSE
no stop	stop	0.1197	0.001*	0.0716	0.1677	TRUE
slow down	stop	0.1358	0.001*	0.0872	0.1844	TRUE

* Indicates statistical significance at the 0.05 level / 95% confidence level



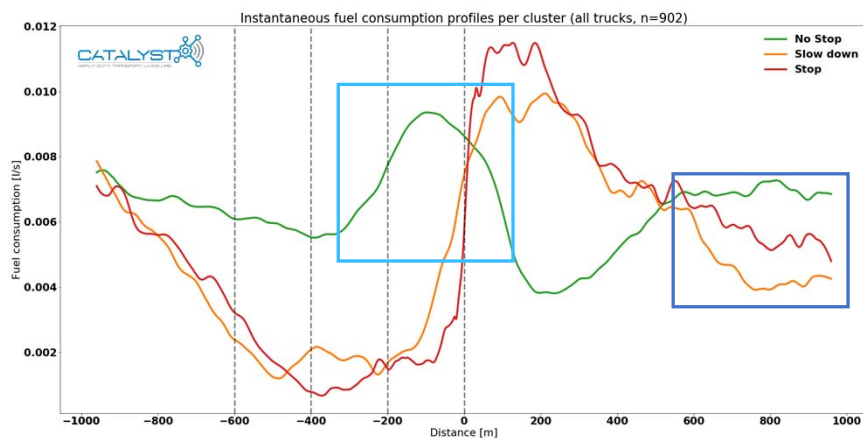
Sample means are provided in the boxplot by means of the diamond
Standard deviation intervals are not displayed to improve readability.

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* An explanation on how to interpret boxplots is available in Appendix A. Appendix B also provides all statistical results in overview.

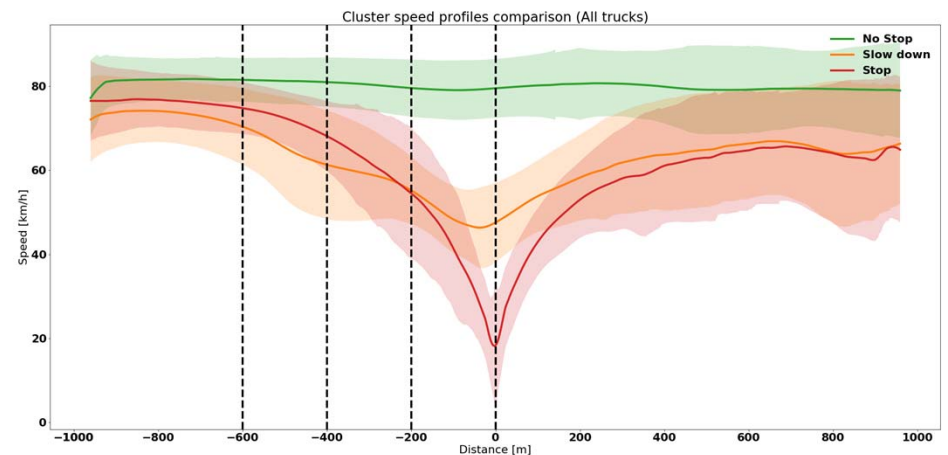
Fuel consumption of heavy-duty trucks: additional observations

Fuel consumption profile for non-stop cluster and effect of unmatched target speeds and fuel consumption over last 400 meters



Surprising fuel consumption before the intersection for the non-stop cluster

At -300 meters to 0 meters to the intersection, an interesting increase in the instantaneous fuel consumption occurs for vehicles in the **No Stop** cluster, as demarcated by the light-blue rectangle. Since the median speed of this cluster does not increase it appears that this increase in fuel consumption is mainly caused by throttle behavior. Potential explanations could be that drivers anticipate the green light (try to 'hit the green/orange' traffic light) or aim to close the gaps with preceding passenger cars or trucks.



Unmatched target speeds over last 400 meters after intersection

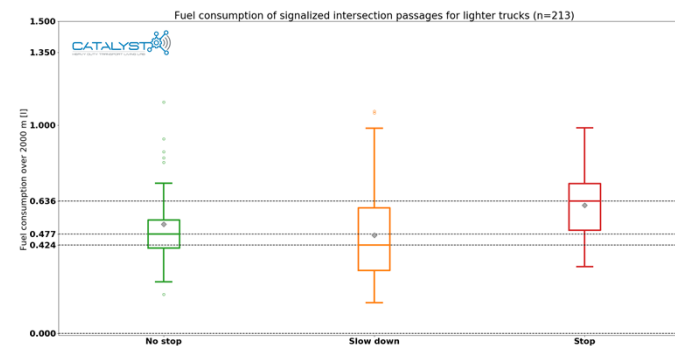
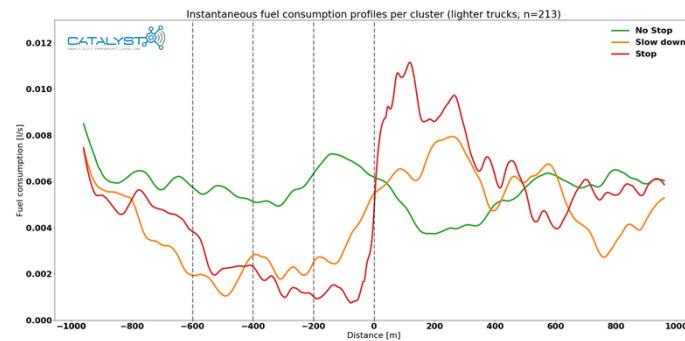
Within the interval from 600 to 1000 meters after the intersection (as demarcated by the dark-blue rectangle), the instantaneous fuel consumption is not the same for all clusters. Additionally a mismatch of the final speeds of the vehicles can be observed (in the right-hand graph). The expectation would be that the **Stop** and **Slow down** cluster would end up in the same region as the **No stop** cluster for both speed and instantaneous fuel consumption.

We have examined the effect of removing this specific data-interval from the overall analysis. The results show that by excluding this interval the difference in fuel consumption between the **No stop** and **Stop** increases with 0.01 l.

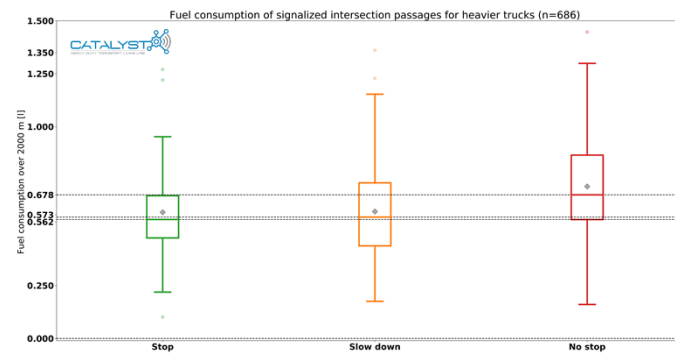
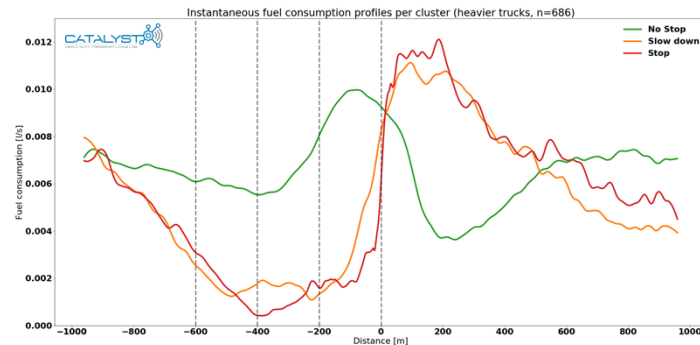
Fuel consumption results: differentiated for heavier and lighter combinations

Median savings are in the same order of magnitude, that is 0.16 l for light and 0.12 l for heavy trucks

Lighter combinations
(up to 30 t)



Heavier combinations
(over 30 t)



Standard deviation intervals are not displayed to improve readability.

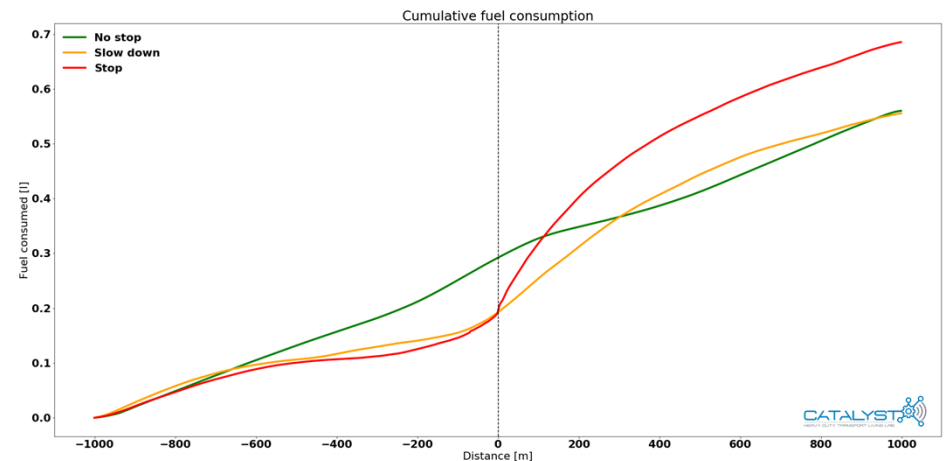
3 intersection passages are not included in this weight split due to unreliable speed profiles. We confirmed that these have negligible effects on overall results

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* An explanation on how to interpret boxplots is available in Appendix A. Appendix B also provides all statistical results in overview.

Interpreting fuel consumption results: investigating fuel consumption before and after the intersection

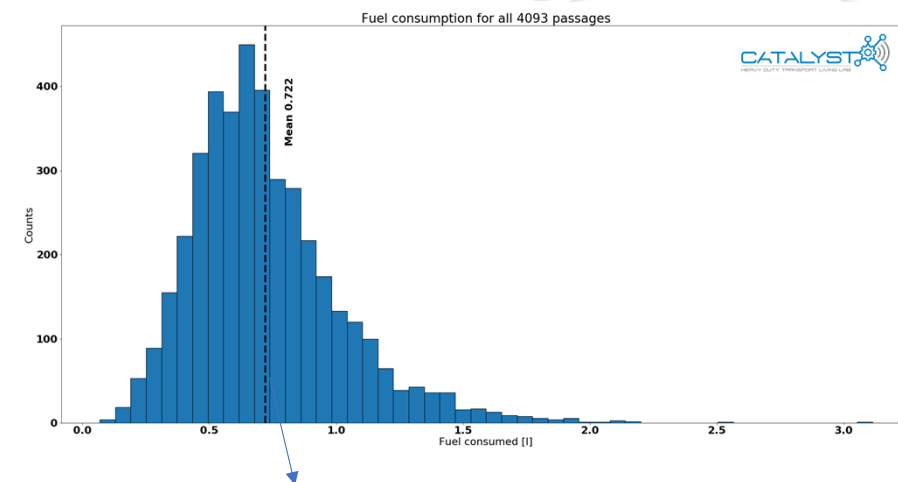
- Before the intersection
 - Fuel consumption is lower for the stopping and slow down cases since throttle is low. Both the slow down and stop clusters have nearly similar consumption values.
- After the intersection
 - After the intersection, both slow down and stop scenarios go full throttle, and it shows as the slope of the fuel consumption curve is the same. A significant amount of fuel is 'saved' (avoided) in the slow down case since the full throttle interval is shorter as it reaches the target speed faster, since it was at a higher speed to begin with.



Interpreting fuel consumption results: many factors impact the fuel consumption along the 2 km passage

Results are in line with earlier research into heavy-duty vehicle fuel consumption

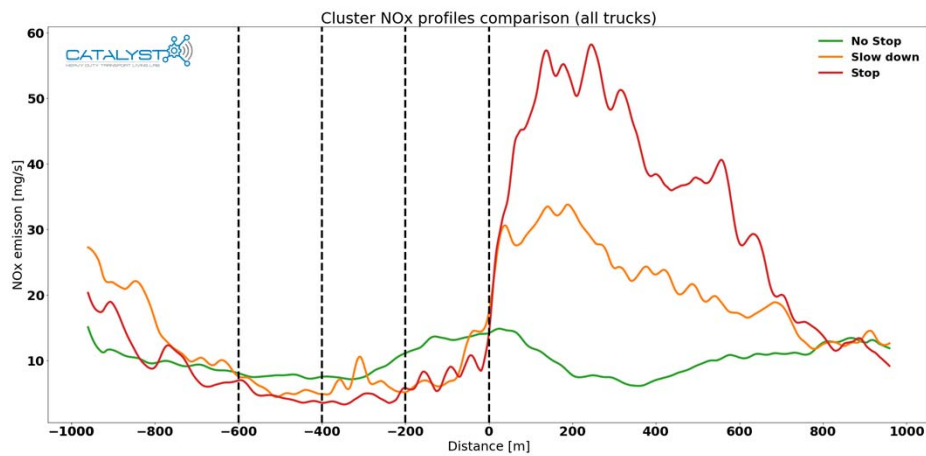
- Savings of 0.12 l of fuel over the 2 km stretch under analysis represents a 16% decrease in the fuel consumption across this distance. These savings scale with the number of avoided stops at signalized intersections in a given route.
- Traffic, driver behavior, weather, and other factors impact the fuel consumption, as well as the vehicle combination weight which is one of the strongest contributors of fuel consumption.
- Specifically, the stop cluster does not represent the maximum consumption. Vehicles also perform a variety of other behaviors such as double stops, stops after the intersection or erratic speed profiles related to traffic and behavioral conditions. These are, in general, related to higher fuel consumption and pollutant emissions. We consider, though, that including those values would not be fair and would make the interpretation of the results more involved.
- Across all intersection passages in the dataset (also including other than straight-driving maneuvers), the mean consumption was 0.72 l over the 2 km stretch, or approximately 0.36 l per km. Considering the fact that we include accelerations, these numbers make sense compared to typical heavy-duty vehicle fuel consumption and emissions, which for the Netherlands are typically around 0.30 l per kilometer. Also the spread in fuel consumption, with values up to 2 liter per 2 km fits to earlier findings regarding congested urban areas.



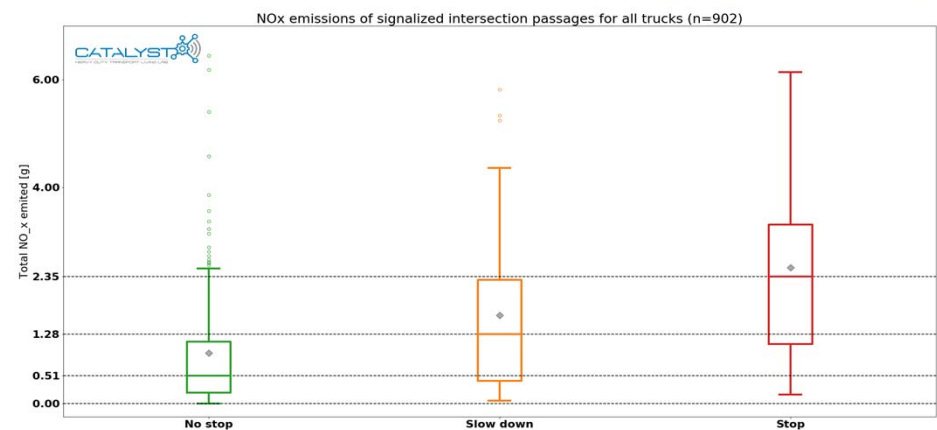
Mean fuel consumption over 2 km stretch: 0.72 l

NO_x emissions results for heavy-duty trucks traversing a signalized intersection

Median reduction of 1.8 g NO_x emitted for the non-stopping scenario compared to the stopping scenario



Interpretation: as may be observed from the graph on the right-hand side, the stop-cluster has a higher median NO_x emission (across the 2 km trajectory under analysis) than the other two clusters. Stopping emits a median 2.35 g of NO_x compared to the no-stop median NO_x emission of 0.51 g, that is an additional 1.8 g NO_x. Especially the full acceleration after the stop, and even the moderate acceleration after the slow-down shows that instantaneous NO_x emissions increase quickly.



Kruskal		
P value = 9e-26*		
Dunn		
Group 1	Group 2	p-value
no stop	slow down	1,90E-12*
no stop	stop	6,00E-23*
slow down	stop	2,30E-04*

* Indicates statistical significance at the 0.05 level / 95% confidence level

Standard deviation intervals are not displayed to improve readability.

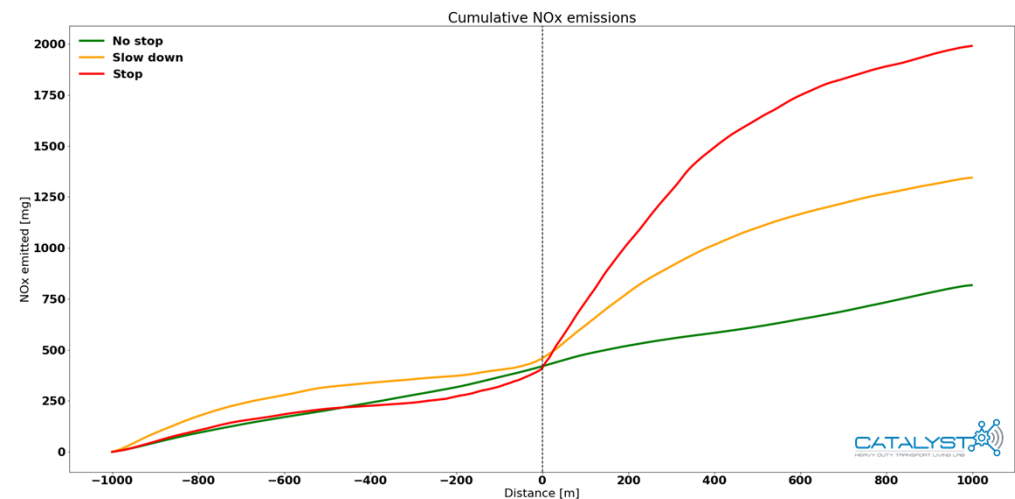
Due to further removal of data with low exhaust gas temperatures the sample size for the NH₃ and NO_x becomes smaller and it is not possible to do the analysis differentiating by weight.



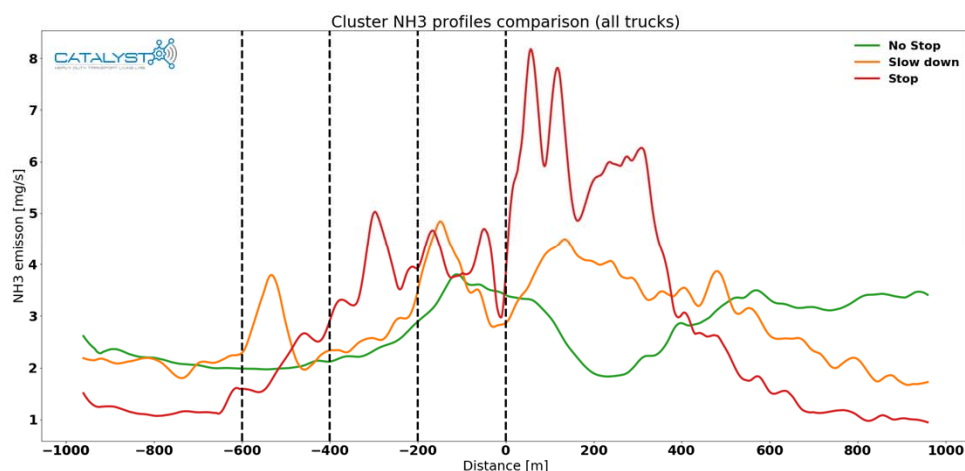
Interpreting and understanding NO_x savings: avoiding a stop saves 1.8 g

NO_x pollutant emissions are especially increased when accelerating after a stop

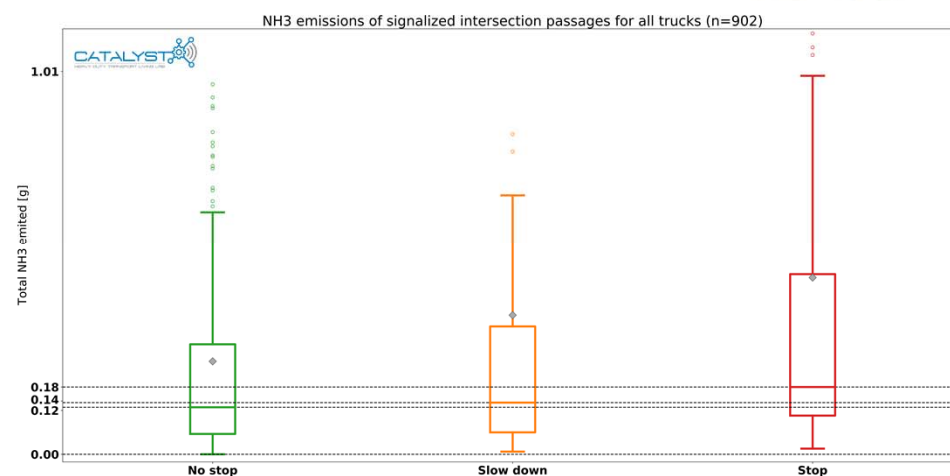
- Emissions of NO_x are stable when the vehicle drives at a constant speed. Stopping at a traffic light translates into an increase of 400% of the emissions during that short period of time, generating an excess of 1.8 g of NO_x . The vehicle emits within the 2 km around the intersection the same amount of NO_x it would have emitted almost 10 km without stopping.
- Contrary to what happens with the fuel consumption, where a balancing effect occurs before and after the intersection, NO_x emissions strongly increase with high throttle and acceleration, making the avoidance of a stop especially beneficial for local air quality.
- The European NO_x emission limit is 0.4 g/kWh. The typical average energy demand for a heavy-duty truck of 35 – 40 tons can be assumed to be approximately 1.5 kWh/km, leading to 0.6 g/km NO_x as limit. As the cumulative plot shows, the trucks remain compliant across the measured 2-kilometer stretch for the no stop cluster while it exceeds this limit in the stop cluster. Therefore minimizing the number of stops becomes key to comply with EU regulations and improve local air quality.



NH_3 emissions: a more challenging measure that requires further investigation



Interpretation: The number of samples in the case of NH_3 is further reduced due to the unpredictability of the NH_3 emissions, which are highly erratic with high fluctuations. Mean and median values are also far apart, making interpretation of the results difficult.



Kruskal		
P value = 0.00078*		
Dunn		
group1	group2	p-value
no stop	slow down	0.109328
no stop	stop	0.000176*
slow down	stop	0.026937*

* Indicates statistical significance at the 0.05 level / 95% confidence level



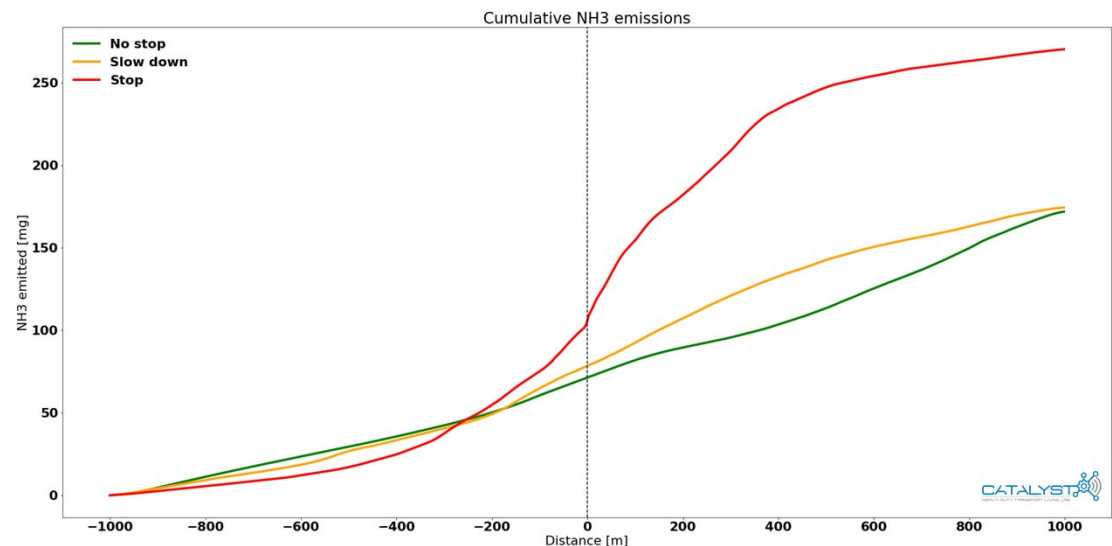
Standard deviation intervals are not displayed to improve readability.

Due to further removal of data with low exhaust gas temperature the sample size for the NH_3 and NO_x becomes smaller and it is not possible to do the analysis differentiating by weight.

HEAVY DUTY TRANSPORT LIVING LAB

NH_3 savings: with caution a median 0.5 g decrease over the 2 km stretch under study has been found

- NH_3 emissions can be erratic due to complex control technology. Results for NH_3 are therefore less reliable than those for fuel consumption and NO_x . With some caution, we find a decrease in emissions of NH_3 through avoiding a stop are in the order of 0.5 g.
- Akin to NO_x emissions, moments of very high throttle are especially critical to avoid undesired NH_3 emissions, as the cumulative emissions graph on the right shows.



7 | Conclusions, limitations and future research opportunities

This section summarizes the conclusions of this study, lists the main limitations of the study and identifies future research opportunities

Main conclusions summarized

Heavy-duty trucks not having to stop at a signalized intersection avoid consuming a median 0.12 l of fuel, and avoid emitting a median 1.8 g of NO_x and 0.32 kg of CO_2 compared to a scenario where they would have to stop, based on data obtained from 5 trucks in real-world driving operations

As the second largest cost factor for a transport operator (after labor costs), there has been a significant effort in reducing the fuel consumption of diesel trucks. In the past decades, the intelligent traffic light emerged as a plausible way to reduce emissions and improve sustainability of road transportation. Modern intelligent traffic lights can not only prevent a vehicle from stopping, but also indicate an optimal speed to approach the intersection, and even provide priority for heavy-duty trucks. In order to assess the potential impact of these systems, good estimations of fuel consumptions and pollutant emissions at signalized intersections are required. Over the years, different figures have been estimated for fuel savings at an intersection attributed to various behaviors. The main question for this research therefore was formulated as follows:

What are the effects of heavy-duty trucks stopping or not stopping at signalized intersections on fuel consumption, CO_2 and NO_x emissions?

- In the current work we did not focus on actual priorities granted at the intersection but looked at vehicle speed profiles for heavy-duty trucks traversing signalized intersections, some of them in the Province of Zuid Holland.
- The fuel consumption and pollutant emissions were logged from the CAN bus and were physically measured at the exhaust (tailpipe) of 5 EURO VI-vehicles from one truck brand that traversed multiple intersections (for a total filtered sample of 902 intersections passages) while performing their actual daily operational tasks, that is, in real-world operations with mean vehicle combination weights of 38 tons.
- We statistically compared three clusters (driving scenarios): vehicles that must stop, vehicles that slow down and reduce their speed, and vehicles that do not change their speed at the traffic light.
- The difference between stopping and non-stopping at the signalized intersection amounts to a median saving of 0.12 l of fuel and 0.32 kg of CO_2 , for the 2000-meter trajectory under study across the logged signalized intersections.
- The difference between stopping and non-stopping at the signalized intersection results in a median saving of 1.8 g NO_x for the 2000-meter trajectory under study across the logged signalized intersections.
- Emissions of NH_3 were also investigated, but no reliable conclusions can be drawn due to erratic emissions caused by either low exhaust gas temperatures or high fluctuations due to complex control technology.

Limitations

The main limitations of this study are listed here, in no particular order

- Specifying (the definition) clusters is difficult and somewhat subjective – especially for the slow-down cluster. Therefore, we have relied mostly on direct comparisons between the non-stop and stop clusters for interpreting the results, and consider the slow-down cluster an intermediate ‘in-between’ cluster
- Data for pollutant emissions were only collected by 5 trucks due to budgetary constraints in the previous Integrator CTT project. A more elaborate study with more trucks across the Netherlands collecting data would yield additional insights to complement this study’s results.
- Although fairly representative for the Dutch heavy-duty truck market, the study was performed on one single brand of trucks. Although the results regarding fuel consumption and pollutant emissions for other truck brands should follow similar trends, for now this is speculative and warrants further investigation.
- We did not control for the engine power of the various trucks in the data set. Since engine power envelopes vary with different engine powers (kW, hp), torque characteristics (N m), and different gear change moments et cetera, the results may vary within the sample of trucks, even if these are from one single brand.
- Most trips (almost 74%) in the dataset have been made by two of the container trucks. Therefore, the data was not really spread evenly across the types of transport operations for which initial data collection took place. Since container truck combinations are also typically on the higher weight end of the spectrum, future research could also benefit from investigating of lighter trucks.
- The indirect (proxy) computations of the vehicle combination weight are not ideal to estimate the results as a function of the load. The exploration of the detailed impact of the weight on fuel and pollutant emissions remains pending for future work.
- Within the analysis we discovered that the three clusters (stop, no-stop and slow-down) did not reach the same target speed after the intersection. An exploratory study was performed to filter the intersections passages more aggressively to obtain a clustering solution that yielded more comparable final speeds. However, the consequence of this strict filtering led to a significantly smaller sample size for the slow-down and stop cluster leaving only approx. 75 and 53 samples per cluster, respectively. Although the fuel savings between the no-stop and stop clusters were bigger in this subsample analysis (± 0.18 l as compared to the 0.12 l in the full dataset) we have chosen not to add these results in the report due to the limited sample size.

Future research opportunities

Some future research opportunities have emerged

- In the current work we did not focus on capturing data from operational iVRIs (intelligent traffic lights), while some of the iVRIs in the Province of Zuid Holland would already be able to provide priority to trucks. In preparation of this work, the Province concluded that the available data structures were not yet sufficient for such an analysis. A future field-operational test could try to close the loop in terms of connectivity and data capture (such that priority requests and priorities granted are properly logged) to estimate how often a truck receives priority.
- Like the remark above, obtaining an understanding of how often a truck receives priority is also interesting within the daily operation of a truck to be able to make a proper cost-benefit analysis of the subscription-based service fees versus the value captured. Moreover within this analysis it is also important to distinguish the vehicles that would have received a green light anyway from vehicles that were actively 'accommodated' by the traffic light controller and therefore resulted in adjusted signal timings. Since avoiding stops for heavy-duty trucks shows some early but promising societal benefits for sustainability and air quality implications, it is important that the business case and upscaling potential is also considered.
- The results show that the instantaneous fuel consumption for vehicles in the no-stop cluster increases significantly just before reaching the intersection; a possible explanation for this is that drivers anticipate the green light. A priority service at iVRIs (combined with time-to-red TTR and time-to-green TTG countdowns) might provide assurance towards the driver that he/she can pass the traffic light without stopping which might reduce the variation in the throttle behavior. Future research may investigate if this translates into (additional) fuel savings.
- The current study does not investigate the effect that giving priority to trucks may have disadvantageous outcomes for other road users in different driving directions at the intersection (longer waiting times, increased fuel consumption and pollutant emissions while standing still and idling). In the future, an integrated network perspective should be taken so that these impacts at the total intersection and intersection network level as well.
- The reduction of acceleration maneuvers at the intersection might limit the road degradation (road deformation, rutting) at the intersection, which would be an interesting societal benefit that is not typically discussed in the context of smart traffic lights. Future research might assess the presence and magnitude of such an effect.
- The reduction of braking maneuvers may reduce wear and tear on the brakes and tires of the vehicle, which in turn may decrease local particulate emissions and reduce maintenance costs of the vehicle. Future research might assess the presence and magnitude of such an effect.



8 | Appendices

Fuel consumption and pollutant emissions of heavy-duty trucks traversing signalized intersections: an exploration using real-world data

Appendix A: interpreting boxplot results

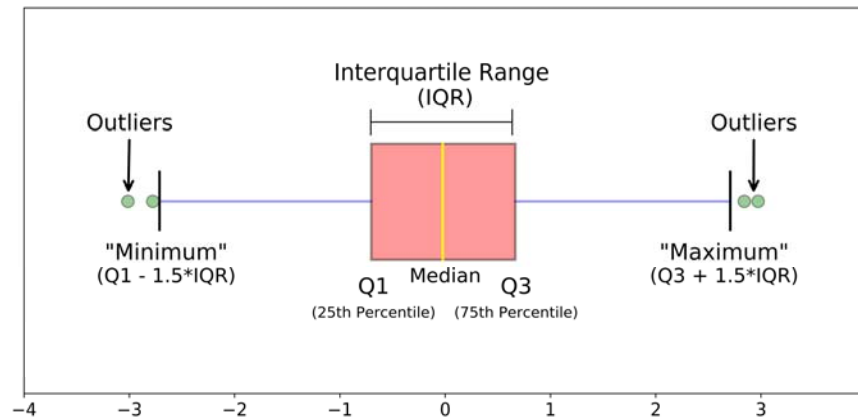


Image credit: <https://towardsdatascience.com/understanding-boxplots-5e2df7bcbd51>

- A boxplot is a standardized way of displaying the distribution of data based on a five-number summary (“minimum”, first quartile (Q1), median, third quartile (Q3), and “maximum”). It tells you about outliers and what their values are. It can also tell if the data is symmetrical, how tightly your data is grouped, and if and how your data is skewed.
- The values within the box (that is – the interquartile range from Q1 to Q3) account for 50% of the data, where the median is the middle value in the data set. The Min and Max values are defined based on 1,5 times the interquartile range. Any values outside of the Min and Max are defined as outliers. Sometimes, means are also shown on the boxplots, as has been done in this presentation
- In the above example, the boxplot is drawn horizontally, but is can also be visualized vertically, as done in this presentation.

Appendix B: statistical results overview

Fuel consumption

Two-way ANOVA | assessing effects on outcomes measures and interaction effects

	Source	SS	DF	MS	F	p-unc
0	mass	26.470	1.0	26.470	307.104	0.000*
1	scenario	19.665	3.0	6.555	76.050	0.000*
2	mass*scenario	0.722	3.0	0.241	2.792	0.039*
3	Residual	364.076	4224.0	0.086	NaN	NaN

Tukey's HSD post-hoc test for pair-wise comparison | fuel consumption, full sample

group1	group2	meandiff	p-adj	Lower	upper	reject
no stop	slow down	-0.0161	0.5893	-0.0552	0.0229	FALSE
no stop	stop	0.1197	0.001*	0.0716	0.1677	TRUE
slow down	stop	0.1358	0.001*	0.0872	0.1844	TRUE

Tukey's HSD post-hoc test for pair-wise comparison | fuel consumption, light trucks sample

group1	group2	meandiff	p-adj	lower	upper	reject
no stop	slow down	-0.0523	0.2831	-0.1333	0.0288	FALSE
no stop	stop	0.0908	0.1495	-0.0237	0.2054	FALSE
slow down	stop	0.1431	0.0083*	0.0308	0.2554	TRUE

Tukey's HSD post-hoc test for pair-wise comparison | fuel consumption, heavy trucks sample

group1	group2	meandiff	p-adj	lower	upper	reject
stop	slow down	0.0036	0.9	-0.0401	0.0473	FALSE
stop	no stop	0.1218	0.001*	0.0701	0.1735	TRUE
slow down	no stop	0.1182	0.001*	0.0652	0.1713	TRUE

- All results of the statistical tests are shown.
- Statistically significant values for a significance level of $p \leq 0.05$ (95% confidence level) are highlighted in red.

NO_x

Kruskal		
P value = 9e-26*		
Dunn		
Group 1	Group 2	p-value
no stop	slow down	1.90E-12*
no stop	stop	6.00E-23*
slow down	stop	2.30E-04*

NH_3

Kruskal		
P value = 0.00078*		
Dunn		
group1	group2	p-value
no stop	slow down	0.109328
no stop	stop	0.000176*
slow down	stop	0.026937*

* Indicates statistical significance at the 0.05 level / 95% confidence level

Connected Transport Corridors

General introduction



Ministry of Infrastructure
and Water Management

Please note – the following introduction slides about the CTC and CATALYST programs are provided as is



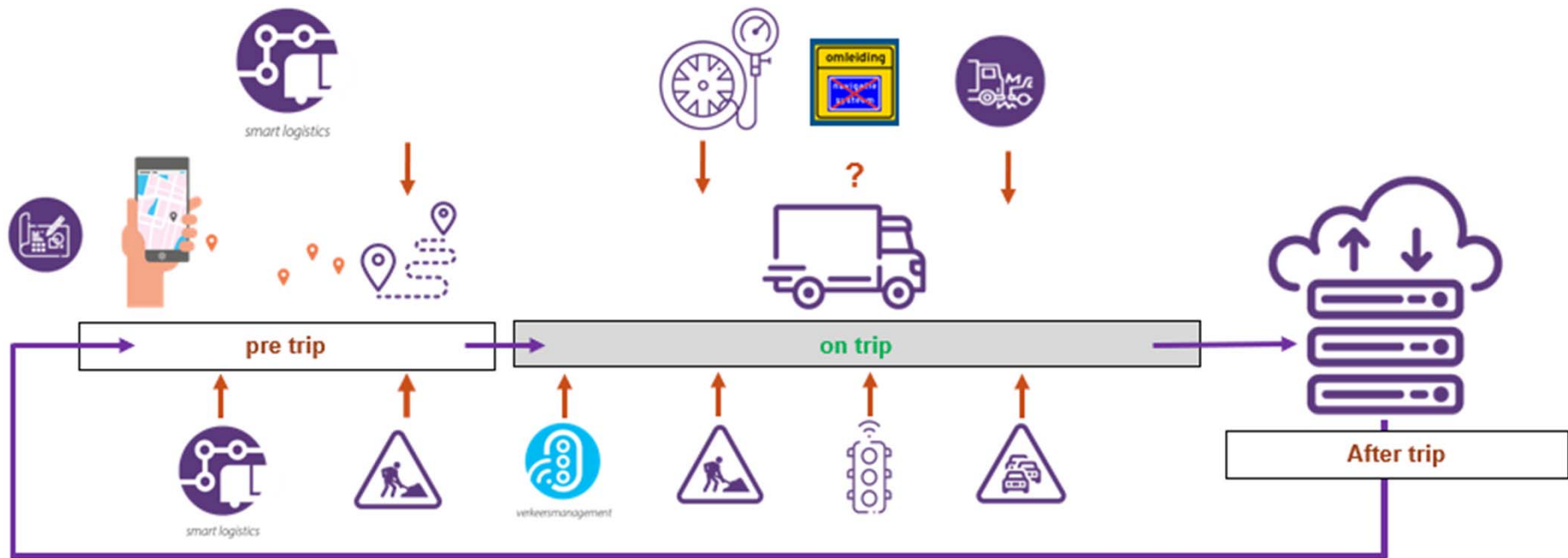
Connected
Transport
Corridors



Connected Transport Corridors

- Nationwide deployment of smart mobility applications in logistics based on data exchange
- Goal: safer, cleaner and more efficient transport
- Not a pilot: achieving lasting impact
- Apply existing technology
- Based on the premise of reciprocity

Connected Transport Corridors





Applications



1. In truck information and speed advices



2. In-truck information about dangerous situations and road works



3. Intelligent traffic lights (iVRIs)



4. Bringing real-time information into the truck

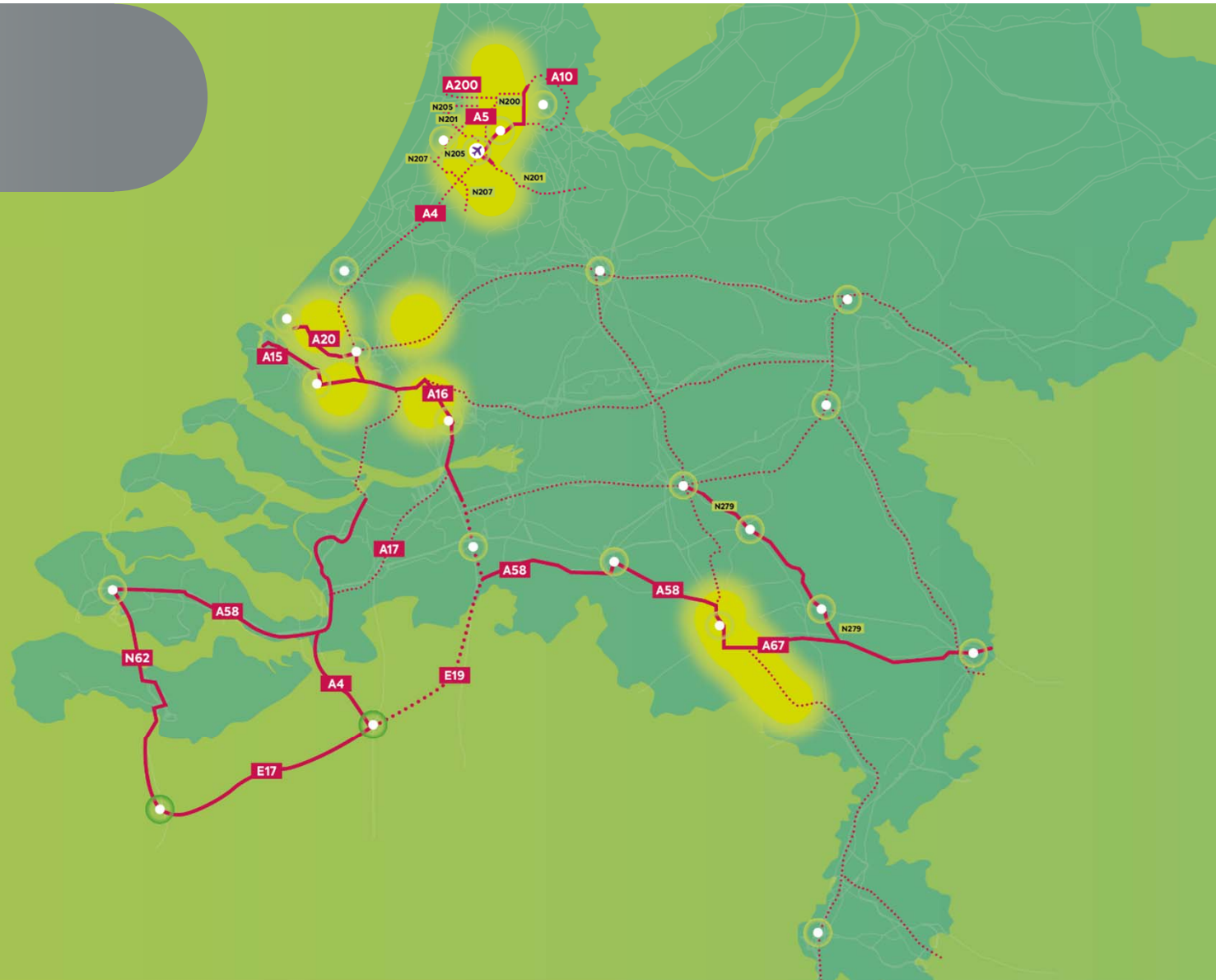


5. Data for planning and routing



6. Bringing road sensor data into the truck

4 Corridors



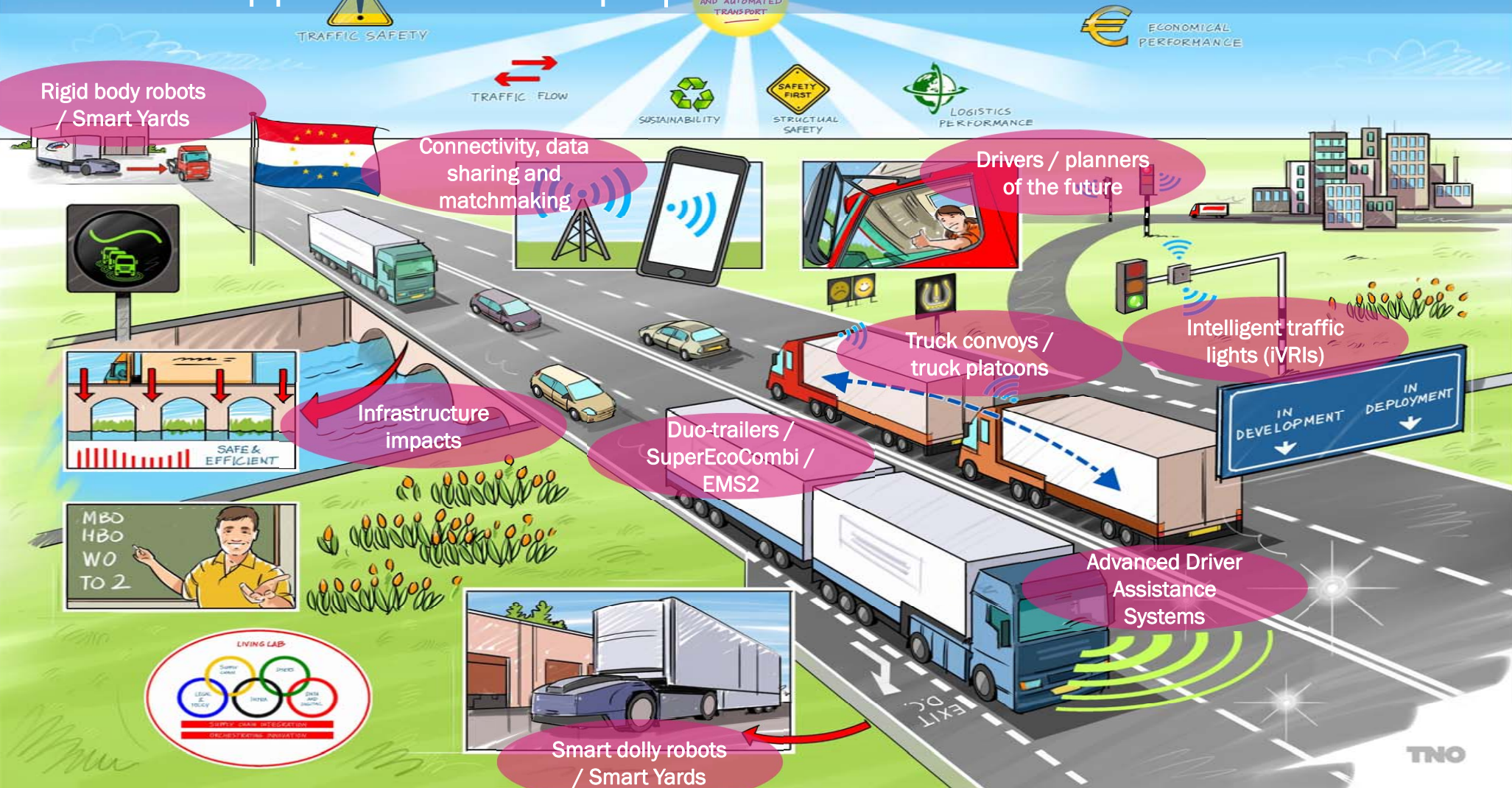
CTC Zuid Holland

Routes with smart traffic lights and priority for trucks::

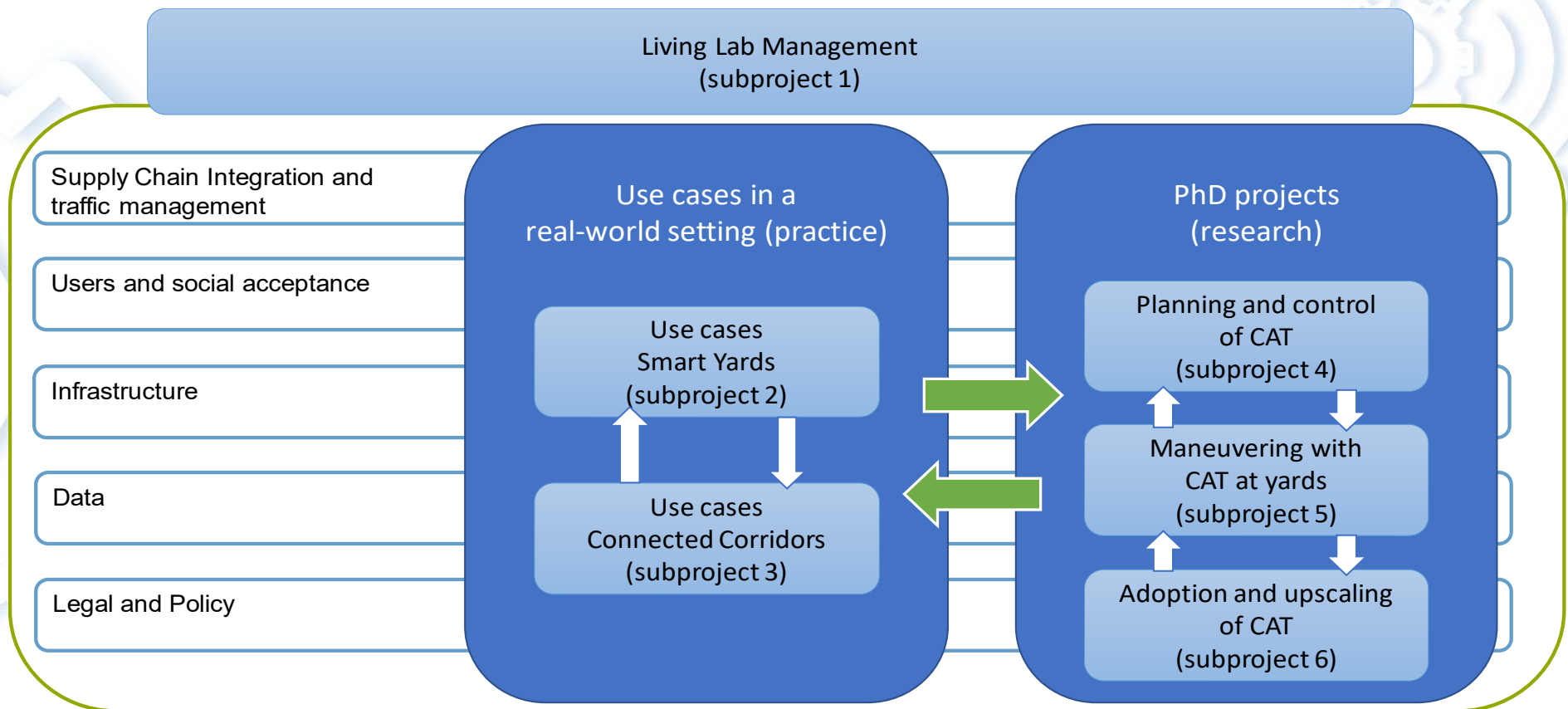
1. Oostland – N209 en N470
2. Westland
3. Waal-/Eemhaven



CATALYST Applications In Scope | 2019 – 2021 – 2023 – 2029



Overview CATALYST Living Lab



What is CATALYST about and what is CATALYST not (yet) about?

Key words

Heavy duty road transport (>12t)	Connectivity (digitization)	Automation (robotization)
Long haul / line haul	Hub-to-hub, yard-to-yard, on-hub and on public road	Wheels on the road / experiments in practice
Fundamental and applied research	Pre-competitive, focused on deployment and social innovation	Multi-disciplinary and multi-stakeholder
Responsible innovation - socially responsible innovation	Reuse and scale existing innovation methods / tools	All levels of education: MBO, HBO, WO, TO2

Light duty road transport	Automation in the warehouse (but includes: the interface of road with warehouse)	Applications that do not bring social value
other living labs blockchain, city logistics, warehouse automation (but includes: the interfaces between	Personal Mobility automation in luxury cars, C-ITS Day1 services for pax cars	Investments in vehicles / hardware / technology (but includes: links towards projects that involve hardware)
Alternative powertrains and fuels LNG / CNG, BEV / PHEV, Hydrogen	No Prince2 / IPMA project	

More information about CATALYST is available at <https://dutchmobilityinnovations.com/spaces/1182/catalyst-living-lab/about#section-about>

CATALYST

Connected Automated Transport and Logistics Living Lab | 28.07.2020



Ministerie van Infrastructuur
en Waterstaat



TKI DIALOG
Dutch Institute for Advanced Logistics



CATALYST
partnership

TNO innovation
for life



UNIVERSITEIT
TWENTE.



Rijkswaterstaat
Ministerie van Infrastructuur en Waterstaat



CATALYST
supporters





More information about CATALYST:
www.catalystlab.nl